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TECHNICAL EVALUATION REPORT

on the

SPECIALISTS' MEETING

on

DYNAMIC ENVIRONMENTAL QUALIFICATION TECHNIQUES

by

Howard A.Magrath
Consultant
2374 Alpine Way
Dayton, OH 45406
USA

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PREFACE

At the 53rd Meeting of the Structures and Materials Panel of AGARD, a Specialists' Meeting on "Dynamic Environmental Qualification Techniques" was held on 28–30 September 1981. It was the purpose of the Specialists' Meeting:–

- To review the state-of-the-art of dynamic qualification techniques and test methods presently applied for military aircraft and helicopters, particularly when carrying external stores;
- To exchange technical information in this field between all NATO countries;
- To review the background and intentions of related Military Standards publications;
- To try to formulate a common basis for dynamic structural requirements and substantiation procedures.

In this Technical Evaluation Report, summaries of the 17 papers presented at the Meeting, and published as AGARD CP-318, are given. Some thoughts on these papers are outlined and general suggestions are made with regard to revisions of existing Military Standards and further improvement and standardization of dynamic qualification procedures.

H.FÖRSCHING
Chairman, Sub-Committee on
Dynamic Environmental
Qualification Techniques

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Technical Evaluation Report on Specialist Meeting I

DYNAMIC ENVIRONMENTAL QUALIFICATION TECHNIQUES

by

Howard Magrath
Consultant to Flight Dynamics Laboratory

1. INTRODUCTION

Background:

1.1 The increase in horsepower of internal combustion engines for aircraft between 1930 and 1940 (from a level of about 575 hp to 1200 hp) aggravated vibrations in engines and airplanes. This led to the development in 1935 of both torsiographs for engines and small, lightweight linear vibration pick-ups for aircraft structures, together with reasonably portable amplifiers and recording oscillographs. The development was sponsored by the U.S. Navy through contracts with the Massachusetts Institute of Technology. With the capability made available by the commercial development of this instrumentation, vibration technology advanced rapidly. The first flight vibration surveys in the U.S. were made in 1936 on the Grumman FF-2 and F3-F Naval airplanes by Massachusetts Institute of Technology and on a Stearman PT-13 airplane by the Air Corps in 1937. The trend of increasing engine horsepower was accompanied by a trend toward all-metal airplanes which resulted in stiffer airplane structures so that the forces of engines and propellers resonated the structures, drastically increasing vibratory amplitudes and stresses. This situation was greatly ameliorated by applying the principles of vibration isolation to engine-propeller combinations but the higher air speeds allowed by the increases in engine horsepower also increased other sources of vibration as well, such as the airborne pulsations induced by the propellers, the air flow disturbances over the surfaces of the airplane, flight through gusts, taxiing over rough ground, etc. Between 1937 and 1944, about 120 cases of vibration in aircraft were investigated by the Aircraft Laboratory at Wright Field; the reports of many of these incidents served as a source of information on the vibration of engines and structures for a wide class of airplanes.

1.2 In most cases equipments for aircraft were purchased separately and competitively from various vendors by the Air Force and furnished to airplane contractors and to Air Force bases for replacement and maintenance purposes. For these procurements, quality assurance tests (to detect variability in manufacture) included a vibration testing procedure which consisted of cycling a constant amplitude of vibration from 10 to 55 cycles and back in one minute intervals for some specified duration. There was no intention in these screening tests to duplicate service conditions.

1.3 In 1945, the Equipment Laboratory at Wright Field set up testing requirements based upon an approximation to service conditions. These requirements used selected reports of vibration investigations conducted by the Aircraft Laboratory. The data were grouped into three categories: aircraft structural vibration, engine vibration, and vibration of elastically mounted assemblies. Maximum amplitudes were plotted on amplitude-frequency graphs and lines enveloping the plotted points were considered to define the most severe conditions of vibration in the three categories of equipment. With the envelopes defined, a test procedure was evolved that was patterned after the structural design approach in which the largest loads under any service conditions become the design loads. For equipment, the largest vibration amplitude applied at resonance conditions was considered to induce the highest possible stress in a specimen. A vibration test under such condition was considered an endurance test. It was estimated that 1 hour of such testing corresponded to 10 hours of service usage.

1.4 Figure 1, taken from Reference 1, shows the original envelope curves. Method 61 refers to vibration of aircraft structure, Method 62 to vibrations of reciprocating engines and Method 63 to vibration isolated assemblies or racks. The procedure specified was (1) a resonance search, with the test item in operation, through the frequency range defined by the applicable Method at an amplitude sufficient to excite resonance, and (2) an endurance test at each condition of resonance at an amplitude defined by an envelope curve. The vibration was applied consecutively along three mutually perpendicular axes of the test item. The time specified was 4 hours along each axis. Methods 61 and 63 were considered to apply also to jet engine powered aircraft based on measurements on four jet-engine powered fighters and one bomber. The Specification AAF 41055, dated 7 December 1945, did not supplant the quality assurance tests routinely followed for instrument panels and reciprocating engine generators, but all equipments were subjected to one of the Methods of the Specification. Reference 1 is an elegantly documented account of this important, early development. This Specification did not apply to electronic equipment. But in 1949 the Navy issued MIL-T-5422, "Environmental Testing of Aircraft Electronic Equipment," which was approved by the Air Force in 1952; at this time Specification 41065 which had been reissued in 1950 as MIL-E-5272, was also approved by all the Services as MIL-E-5272A so that both electronic and non-electric equipments were then covered by specified test procedures.

1.5 Between 1950 and 1960, jet engines increased in size and power, missiles and rocket engines were developed, intense sound fields were created and airborne electronics applications grew explosively. There was a proliferation of specifications with overlapping requirements. In 1960 a study recommended that a single environmental test document be prepared. MIL-STD-810 (USAF) subsequently was issued on June 14, 1962. In 1967, updated requirements and acoustic testing requirements were placed in MIL-STD-810B. Requirements for the gunfiring environment (Ref. 3) were included later by amendment in 1969.

1.6 The development of a large variety of external stores for airplanes and helicopters resulted in electronic instrumentation pods, dispenser pods, etc. that in many cases contained internal equipments. Qualification test requirements were developed for equipments installed in externally carried stores on aircraft; and two additional test requirements were adopted covering whole-store testing for airplanes

and for helicopters. These requirements (Ref. 4) together with revisions to the gunfiring requirements and to the effects of ground handling as well as the introduction of two level testing, functional and endurance, were put in MIL-STD-810C, issued in 1975.

1.7 In 1979 further revisions to these 810C requirements were initiated, with considerable interest being shown by representatives of the Federal Republic of Germany and France (Ref. 5).

2. OBJECTIVES OF THE MEETING

2.1 The principal purpose of the Meeting was to review the state-of-the-art in qualifying external stores for military aircraft from the dynamics standpoint.

2.2 A further purpose was to review vibration analysis techniques and developments in vibration prediction methods.

2.3 The Meeting followed a prior AGARD Meeting in 1979 on a broader aspect of this subject: dynamic qualification procedures for aircraft and spacecraft structures and equipments (Ref. 6).

3. SUMMARY OF CONTRIBUTIONS

Summaries of the 17 papers presented at the Meeting are given below.

3.1 "Development and Use of Dynamic Qualification Standards for Air Force Stores," by Alan H. Burkhard and Otto F. Mauer, Air Force Wright Aeronautical Laboratories, WPAFB (U.S.).

The paper was presented by Dr. Burkhard. Following introductory remarks on standardization in the U.S. Air Force, which was mandated by Public Law to "achieve the highest practicable degree of standardization of items and methods used throughout the Department of Defense", Dr. Burkhard warned of three possible adverse effects of having a Standard: the need to keep the Standard up-to-date, the danger of applying the provisions of the Standard in a "rigid manner", and the resistance to change engendered by the very existence of specialized testing facilities. The paper goes on to quote a report of a Task Group on Specifications and Standards in response to the charge that Specifications and Standards cause delays, poor performance and excessive costs. The Task Group found, to the contrary, that in most cases the Specifications and Standards were misinterpreted or misapplied, and as to rigid requirements increasing costs, the documents were found to contain much more flexibility than appeared to have been used in practice. Nevertheless, the current trend, according to the paper is toward a "tailored testing approach" so that test levels and durations will be determined by the "equipment acquisition community." Evidently, the "tailoring" is going beyond, for example, the adjustable levels W_1 and W_2 and the variable frequency points f_1 and f_2 that permitted "tailoring" in MIL-STD-810C (Ref. 7).

But the main thrust of the paper was directed to the testing of stores carried externally on aircraft. Store vibrations arise from the motions of the airplane (due to maneuvers, runway roughness, gusts) which excite the low frequencies, 5 to 100 Hz, and from the aerodynamic flow around the store and the related sound pressures from acoustic sources (turbulence generally) which excite the surface panels of the store at high frequencies, above 150 Hz. The qualification tests for assembled stores are thus in two parts, the first using whole- store excitation by electrodynamic shakers, the second being an acoustic test using a reverberant chamber. The paper lists problem areas that will be addressed during the on-going revisions to MIL-STD-810C. These are gunfiring effects on stores, store buffetting, store launch, stores in open weapon bays and stores with cavities.

3.2 "Problems in the Ground Simulation of Dynamic Responses Induced in Externally Carried Stores During Flight," by J. Homfray, Cape Warwick Ltd., U.K.

In his paper, Mr. Homfray emphasized the difficulties experienced in testing large, low-density stores. He noted the shortage of points at which the stores could be excited and the complexities of suspending them. It seems that the supporting rig plays an important part in polluting the responses in ground tests. In relation to MIL-STD-810C ground tests, two stores he had tested gave relatively different results in the high frequency and low frequency regimes and also in relation to flight results. Generally, however, most ground test levels were much higher than the flight levels (Fig. 2) and on the large store which had fins the low frequency levels in flight were 2 orders of magnitude less (Fig. 3). The spectra of flight and MIL-STD-810C tests were, nevertheless, somewhat similar and peak values tended to agree although there was evidence of cavity resonances not covered yet in the Standard. In all, it pointed to the gross enveloping characteristics of MIL-STD-810C, which is all it lets out to do - but the size of the ground/air differences pointed up the need for the tailored approach mentioned in Dr. Burkhard's paper.

The paper suggested that several of the difficulties in the low frequency regime could be avoided by a different approach to testing which would involve amplitude rather than force excitation. The idea of constructing a rig having aircraft characteristics, and exciting the rig rather than the store seemed attractive.

In the discussion it was mentioned that the relatively small size of the data sample from flight trials indicated the need for a flight/ground factor when clearing equipment. The aerodynamic loads put in by fins was also pointed out and as yet this did not seem to be covered in MIL-STD-810C. -- D. R. B. Webb, Royal Aircraft Establishment, U.K.

3.3 "Progres Dans L'Elaboration Des Programmes D'Essaid' Environment Mecanique" by Michel Coquelet, Centre d'Essais Aeronautique de Toulouse, France

In his paper, M. Coquelet listed the various standards he had worked with but which had deficiencies. Accordingly, they had decided to build up a data-bank based upon measurements in 12 aircraft. It was intended to use these data in drafting an international document ED 14A/D160 which was an ISO standard and had included the USSR. An international specification seemed paramount as a tool in communications, business, and export. He also said that specifications should not be used rigidly and alternative real data used whenever possible. He gave examples of the data already gathered from some aircraft in the data-bank exercise. In relation to one of the specifications he had examined (DO 160A) there was a very wide variation in results. On some aircraft low frequencies were much higher than previously experienced while close to engines much higher high frequencies were measured. Together this confirmed the need for modern data.

For external stores, the need to compress the test time-scale was the main problem. For example, testing for 1,000 hours is not practical. He then described three main factors relevant to the compression process: more severe spectra from enveloping; damage equivalance using an accumulative damage law; and the removal of non-damaging frequencies from test envelopes. He closed by re-emphasizing the importance of international collaboration. The questioning expressed interest in how this collaboration had been organized and coordinated within cooperating countries. He indicated the relevant organizations that had been involved. -- D. R. B. Webb, Royal Aircraft Establishment, U.K.

3.4 "Qualification of Equipment for Gun Fire Induced Vibration," by A. Peacock, British Aerospace, U.K.

In this paper, the author discussed the tests that were conducted to qualify equipment for withstanding the gunfire environment in the forward section of the Tornado MK-1, a twin engine, two-seat supersonic airplane. Mr. Peacock's paper explained that up to about 1960 MIL-STD-810B (U.S.) and BS G.100 (U.K.) gave satisfactory results for equipment clearance testing and no additional gunfiring tests were required. After 1965, introduction of more powerful guns, the miniaturization of electronic components as well as conflicting requirements among standards led to a decision to develop test levels by measurement.

The program to do so was guided by gunfiring tests on a rig consisting of the structure of the forward part of the airplane back to and including the pilot's compartment, tests using an airplane tied down on a gunfiring range (butt tests), and tests on an airplane in flight. The flight vibration levels were broadly similar to those induced in the firing tests in the butts (Fig. 4) and there were no significant differences in the levels with changes in airspeed (400-650 knots at 15,000 ft. altitude) or manuever g (½ -4g at 450 knots).

A comparison of vibrations measured in flight with the test spectra given in MIL-STD-810B-810C and BAe is shown in Fig. 5. The MIL-STD-810C spectrum is considerably more severe than that given by the flight measurements.

As a result of the testing program, a procedure for qualifying equipments was worked out. First, the test levels given in MIL-STD-810C, Method 514.2 (the test levels for equipment in jet-powered airplanes) are defined as the "normal" test levels and the levels given by Method 519.2 as "gunfiring" levels. For an equipment item that is safety critical, the test level will be the greater of the "normal" or "gunfire" level depending on the location of the equipment. For equipments that are not safety critical, the test spectra will not be less than the "normal" level, but can be less than the "gunfire" level. For regions of the airplane where "gunfire" levels are significantly above the "normal" vibration levels, equipments so located will be anti-vibration mounted. Finally, only one vibration test, at either "normal" or "gunfire" level, will be conducted on each equipment.

The author further recommends that (a) gunfiring spectra, now relying entirely on blast and distance from the gun muzzle, be modified by taking into account structural stiffness and damping, and (b) that further theoretical and test work be done to optimize the design of gun blast deflectors.

3.5 "Dynamic Qualification Testing of F-16 Equipment" by H. E. Nevius and W.J. Brignac, General Dynamics, U.S.

This paper presented by Mr Nevius is in two parts, the first dealing with the effects of gunfiring, the second with "non-gunfiring" vibration.

Gunfiring Aspects:

A principal concern was the effect of gunfiring on equipment located in the vicinity of the gun muzzle. The location of the gun in the airplane is shown in Figure 6. The gunport is adjacent to the aft equipment bay where equipments receive the highest vibration in the airplane due to muzzle blast at the gunfiring rate of 100 rounds-per-second. The forward equipment bay receives little gunfiring vibration. There was also concern for the pilot when subjected to gun blast noise. Gunfiring vibration test requirements were originally developed from measurements made on the prototype YF-16 on the ground. Narrow band and psd frequency analyses were made to derive a correlation between vibration and distance from the gunport, Figure 7. The vibration qualification test consisted of a sweeping sinusoid combined with a random background level. A normalized frequency spectrum for the test is shown in Figure 8. The values for the sinusoidal and random levels are obtained from Figure 7. Test duration is given as one hour of sinusoidal sweeping per axis plus six resonance dwells at the harmonics of 5 minutes each. Gunfiring vibration measured in flight on the F-16A (single seat) and F-16B (two seat) airplanes confirmed the adequacy of the prediction procedure derived from the ground gunfiring tests on the YF-16.

Other results of the gunfiring investigations were a proof of the adequacy of the fuselage structure to withstand gun blast pressures, the need to equip the instrument panel with vibration isolators to protect the instruments and the need to add sound insulation to the cockpit sidewalls to reduce cockpit noise levels.

Non-Gunfiring Vibration

Measured flight vibration data from the F-111C and YF-16 airplanes were combined with criteria and equations in MIL-STD-810C to predict the initial non-gunfiring vibration qualification test levels for equipments in nine zones of the airplane. In this case, MIL-STD-810C is used as a prediction method. In addition to the random vibration requirements for equipments in all zones of the aircraft, sinusoidal vibration requirements were imposed on equipments located on the tips of the wing, tail and fin. The sinusoidal tests were supplementary requirements representing the structural response of the basic modes of vibration of wings and empennage. All predicted levels, Figures 9 and 10 were then compared with vibration measurements taken in flight for all usual flight conditions from take-off to landing. Levels in each zone were found to be adequate except in zone 1A (from the fuselage nose back to the cockpit) where at low frequencies (15-100 Hz) levels did not exceed 0.001 g^2/Hz and the level of the random spectrum was reduced from 0.02 g^2/Hz to 0.002 g^2/Hz, Figure 11. In the cockpit portion of zone 1A (aft of the forward equipment bay) levels at low frequency for all flight conditions were reported to be negligible.

Flight vibration measurements were obtained for external stores carried on a fuselage center-line pylon and inlet pylons. A laser designator pod weighing 320 lbs. mounted on an inlet pylon experienced vibration levels four times lower than MIL-STD-810C levels and very small vibrations at the low frequencies, while a much lighter pod (70 lbs) on the same pylon showed much larger levels at the low frequencies. The store measurements, in general, indicated that MIL-STD-810C levels are adequate for missiles and bombs but indicated a need for new prediction procedures for light-weight, low-density stores such as pods.

3.6 "Development of Vibration Qualification Test Spectra for the F-15 Aircraft," by G. R. Waymon, McDonnell Douglas, U.S.A.

Mr Waymon's paper is also a two-part report - one part being the prediction of test levels in the design stage, the other part being an investigation of vibration measured on an early F-15 which was the basis of confirming the predicted levels.

Prediction of Qualification Test Levels

For the prediction process, the airplane (Fig. 12) is divided into ten zones. For each zone there are two requirements, a sinusoidal test requirement for non-electronic equipments, and a sinusoidal plus random requirement for electronic equipments. Test levels are predicted for each zone of the airplane for four conditions: flight and maneuvers, gust encounters, landing and taxiing and gunfiring. For flight predictions, the Mahaffey-Smith method (Ref. 8), which relates external sound pressure levels to structural vibration, was used. For gust encounter, the method of Houbolt (Ref. 9) was used; in this method the vibratory accelerations are calculated by power spectral density methods for a representative cruise condition in the air superiority mission. For taxi, two 2-inch amplitude bumps (1-cosine) were used as excitation for a flexible body idealization of the airplane using an analog computer. For gunfiring, test levels developed from measurements on the F-4 Phantom were used. Gun muzzle blast pressures were ignored as not affecting equipments in the avionic bays because of the gun location and the use of blast diffusers.

The levels thus predicted for each zone were considered to be "average" levels and were adjusted by a series of factors to arrive at qualification test levels (except for levels predicted for gust encounter, landing and taxi which are short duration amplitudes and require no factoring). The factors are three in number for predicted test levels: a factor of 1.5 to account for not predicting the most severe environment; a factor of 1.7 for conversion of sinusoidal data from root-mean-square to zero-to-peak for 1/3 octave bands; a factor of 1.3 to account for testing separately along each axis whereas vibration occurs along all axes simultaneously in service (Ref. 10). The product of these factors, 3.3 for sinusoidal levels and 2.00 for random vibration levels (in the latter case the second factor above is zero) when applied to the results of the prediction methods, yields the predicted performance test levels. To get the predicted endurance test levels, another factor is applied to the performance test levels. This factor is one based upon equal fatigue damage under airplane use and test duration and it increases the qualification test amplitudes while decreasing the test time from its value under service usage. The predicted performance and endurance test levels for sinusoidal and random testing for zone 1 in the F-15 are shown in Figure 13.

Flight Measurement Program

The flight vibration survey used about 50 triaxial accelerometers. Thirteen conditions were investigated including engine ground run, taxi, takeoff, climb, descent, approach and touchdown. Six airspeeds were investigated from M=0.8 to M=2 at 10, 20 and 40-thousand foot altitudes. Vibrations were also measured during wind-up turns, rolling pullouts, symmetrical pull-ups, afterburner acceleration, speed brake deceleration and missile and store separations. Gunfiring was investigated during firings on the ground and in-flight at the three altitudes and six airspeeds. Data were printed on strip-charts and selections were made for analysis. Two frequency/amplitude analyses were made: one-third octave for sinusoidal data and psd's for random data. For each measuring point on the airplane, data were collected from every flight condition and a composite plot was obtained by overlaying.

After reviewing all spectra for each measuring location, all locations that showed similar levels were collected into groups. These were used to define the zoning of the airplane. These composite spectra were than multiplied by two of the factors used on the predicted data, the factor of 1.5 that accounts

for not measuring the most severe environment, and the factor of 1.3 that accounts for measuring separately along each axis when vibration occurs along all three axes simultaneously. This factoring of 2.00 for sinusoidal data and 4.00 for random data yields the performance test levels; application of the amplitude exaggeration and test time compression factor gives the measured endurance qualification factors, both sinusoidal and random. The performance and endurance qualification test levels based on flight measurements are shown in Figure 14 for sinusoidal and random test levels.

As shown by Figures 13 and 14, the measured data had a large effect on both random and sinusoidal predicted test levels. The measured psd levels above 300 Hz were larger than the predicted levels by an order of magnitude and the measured sinusoidal levels were very much larger than the predicted levels at frequencies above 1000 Hz and larger below 50 Hz. In the intermediate range of frequencies, 50-200 Hz, the measured levels were lower. In spite of the rather large difference in levels in the intermediate frequency range, the authors conclude that the predicted levels, the original qualification test levels, were adequate because most of the critical frequencies of equipments fall in the 50-200 Hz range, thus making the tests effectively conservative.

3.7 "Equipment Vibration Qualification for Harrier and Hawk Aircraft," by D. C. Thorby, British Aerospace, U.K.

The author of this paper describes the highlights of working with the British Standard 3G.100 (1969) in qualifying equipments for the Hawk, an advanced jet trainer, and the Harrier, a VTOL airplane. The Standard requires: (a) initial and final resonance searches, (b) wide-band random testing for endurance tests (preferred), (c) choice of alternate test levels from 0.0005 to 0.05 g^2/Hz constant power spectral densities, in two frequency ranges 10-60 Hz and 60-1000 Hz; (d) alternate methods for endurance tests, sinusoidal sweep, narrow-band random or resonance dwell, but note (b); (e) endurance test duration based on equipment usage but a maximum of 50 hours, divided 20/20/10 along vertical, lateral and fore-and-aft airplane axes. In applying the Standard, equipment suppliers are required to consult with the procuring agency if they elect a test method other than random testing; and suppliers' test proposals are checked over by a Structural Dynamics specialist. Because of the alternate test levels (Fig. 15) and the existence of other specifications requiring sinusoidal testing, a set of rules was devised which converts a random signal to an "equivalent sine wave." The equivalence (Fig. 16) is based upon fifth power of the amplitude damage (Miner's Law) and upon the rms amplitude of the sine wave being equal to 1.27 times that of the random wave. This amplitude is then multiplied by an exaggeration factor of 2.09. The equivalence becomes $d = 1184 \sqrt{S/Qf_n^3}$ millimeters peak sinusoidal vibration where S is the constant power spectral density (g^2/Hz) of the random wave, Q is the resonance factor of the vibrating system and f_n is its resonant frequency.

In the design stage of the airplane, equipment is procured based upon a selection of test levels chosen by past experience, but as soon as possible vibration measurements are made in flight and vibration test levels are adjusted accordingly. The paper describes practical measures of selecting representative spectra, the problem of non-stationarity in data, and the importance of identifying malfunctions of equipments, that is, the proper level for performance testing. With respect to endurance testing, the author believes that overtesting may be permissible and that there is much to be said for the old, very severe, sinusoidal tests for seeking out equipment design oversights, such as poorly supported components. The British Standard appeared to work well for the Harrier and Hawk programs.

3.8 "Acoustic Noise Test as Part of the Dynamic Qualification Program in Aerospace," by G. Bayerdorfer IABG, Germany.

In this paper the acoustic test is looked into as a supplementary test for both large equipment assemblies and even for small, high density electronic boxes. As an illustrative example, an electronic device (the size and volume were not given) was tested acoustically in 3 chambers of differing volume: 5, 200 and 800 m^3. The power spectral densities of the sound fields showed the usual drop in energy at low frequencies in the test chambers. The psd's of response of the test item are similar for all chambers since the lowest natural frequency of the test item appears to be well above the cut-off frequencies of the three test chambers, 40, 100 and 200 Hz for the largest to the smallest chamber. The author concludes that small test items do not need the lower end of the test spectrum (at 63 Hz) as shown in MIL-STD-810C (but this Standard is mainly for externally carried aircraft stores) but that large items do need exposure to low frequencies (31 Hz), in a sound field of high modal density. Hence, the paper finds that two test spectra are needed, one for low frequencies (undefined) and the other for higher frequencies, 125-2000 Hz, the spectrum shape being identical with that in ISO D15/2671.2 specification.

The recommendation that acoustic chamber testing be used for electronic packages and equipments is a good one, since acoustic testing allows excitations above the traditional 2000 Hz where malfunctions in miniaturized electronic components have reportedly been induced.

3.9 "Vibration Qualification of External A/C Stores and Equipment," by M. Steininger and G. Haidl, Messerschmitt-Bolkow-Blohm, Germany.

This paper is in two parts - the first part concerns the prediction of vibration qualification test levels and compares the U.S., U.K. and French Government Standards. The second part of the paper discusses points arising in determining vibration levels for three different external stores as well as factors involved in defining laboratory qualification tests. Also included is a discussion of special environments largely due to whole-store testing.

Methods of Level Prediction

In the first part of the paper, comparisons among the three Standards, MIL-STD-810C (U.S.), BS 3G.100 (U.K.) and AIR NORME 7304 (France) highlight the differing approaches to assuring failure-free equipments for aircraft (Fig. 17). MIL-STD-810C adapts the vibration levels and test procedures to individual cases

(those cases may be equipments by vehicle class, e.g., helicopter, propeller or jet powered airplane, missiles, etc., or by equipment type, e.g., external stores) by evaluating a series of basic parameters (the number of service missions, maximum dynamic pressure, store density and geometry, mounting configuration etc.) so that for practically every case, or store, an individual test spectrum can be defined. In the British Standard, the test levels are selected from a series of standard test levels in accordance with equipment location, flight condition and past experience and modified later by vibration measurements on the airplane. In the French Standard, test levels are dependent on equipment location and weight, and by reference to a data bank, a form of corporate memory. The parameterization scheme followed in MIL-STD-810C permits it to be used as a vibration prediction method and it is often so used, as it is in this paper, even though that may not have been the original intention of its authors.

Vibration Measurements and Analysis for External Stores

This second part of the paper gives accounts of measuring the vibration environment on an air-to-air missile, on an instrument pod and on a large, heavy missile and launcher. In all these cases, the measured vibrations, when converted to laboratory qualification test levels, exceeded the levels defined by MIL-STD-810C. For the air-to-air missile, the difference, measured by the overall RMS vertical acceleration at the tail section of the missile was 24%. In the case of the instrument pod carried at the mid-span of the wing, a sharp increase occurs in the psd at frequencies below 200 Hz over MIL-STD-810C levels as shown in Fig. 18. This is ascribed by the authors to the excitation of a low-damped, wing-torsion-store pitch mode. In the case of the missile and launcher, the vibration levels derived from measurements are more consistent with MIL-STD-810C if the launcher is considered a pylon (procedure I A) rather than being considered as an external store (procedure II A). The authors conclude that for external stores the range of testing frequencies should start at 4 Hz, particularly for heavy stores.

The authors indicate that, in the relation between flight measurements and qualification test levels, certain factors are applied to measured amplitudes to account for the possibility that the most severe environment was not measured and that sharp peaks were not enveloped. In the case of the air-to-air missile, the overall factor on the maximum measured rms acceleration appeared to be 2.00 or approximately 3 db. With regard to the "fatigue factor", relating service usage time and the shorter laboratory testing time, the factor must assure that the fatigue damage accrued under actual service usage time and the laboratory testing time is the same. This involves Miner's hypothesis of cumulative fatigue damage (Ref. 11) and fatigue damage/time scaling techniques in which damage is proportional to some power of the fatigue factor. In the form that this factor is found in MIL-STD-810C, service usage time is expressed by a constant representing the fractional part of an hour per airplane mission that is spent under certain environmental exposures; for high q flight, this constant is 1/3, representing 20 minutes per hour per mission of high q flight. The authors believe this should be reduced to 1/20, representing 3 minutes per hour mission. Regarding the power to which the fatigue factor is raised, expressed as the reciprocal of a constant related to the slope of a logarithmic plot of an applicable S-N curve, the authors agree with MIL-STD-810C and AIR NORME-7304, France, on the value of $\alpha=4$ but believe that the value of 2.5 given in BS 3G.100 (U.K.) is too low and results in endurance test levels that are comparatively high. Values of this constant used in the case of the F-15 airplane tests was 4.35, giving a range of quoted values of 2.5 - 4.35. If, for example, the random vibration level is doubled, the duration of the endurance test is about 3½ times longer for $\alpha=2.5$ than for $\alpha=4.35$.

The authors point out that the flight environment for stores can be increased significantly by vibroacoustic phenomena in store cavities, and by impulsive loadings from missile launching and ejections from dispensor pods. Consideration of these environments are being addressed in MIL-STD-810D according to Dr. Burkhard's paper.

In summary, the authors recommend that the testing range for stores be lowered to 4 Hz to take into account excitations of the low, structural modes of the airplane; that further zoning of stores be considered to provide a more realistic distribution of amplitude levels along the store; that the "fatigue factor" constant representing the proportion of mission time spent in high q flight be reviewed; that agreements on store test set-ups, test procedures and testing times be sought so that test results will be more directly comparable; and that the results of flight vibration measurements be broadly disseminated.

3.10 "Aircraft Fuel Tank Slosh and Vibration Test," by Wolfgang Raasch, IABG, and Helmut Zimmerman, VFW, Germany.

In this paper the authors describe their experiences in qualifying external fuel tanks from the vibration standpoint in accordance with Specification MIL-T-7378A (USAF).

The two fuel tanks were designated subsonic and supersonic. The subsonic tank had a capacity of 1500ℓ and the supersonic tank a capacity of 1000ℓ Each tank was baffled and had three compartments.

Test requirements are a simultaneous slosh and vibration test while two-thirds full (but with a full center section) for 25 hours, and a similar test with the tank completely full for 10 minutes. During tests, tanks are pressurized to 15 psi. Slosh amplitude is ±15 degrees in pitch about the lateral axis through the tank c.g. at 16-20 cpm (0.267-0.3 Hz); the vibration is 0.020 in. double amplitude at a frequency of 2000 cpm at the tank attach points to the airplane and a minimum average double amplitude of 0.032 in. between the top and bottom of the tank at the bulkheads below the attachment points of the tank.

The test rig (Fig. 19) was a large platform pivoted about a lateral axis at the midpoint of its length and driven in rotation by a strut offset from the pivot. The tanks were instrumented with ten accelerometers and two strain gage bridges.

In running the tests, some anomalous results were obtained. It was found that resonance of the test rig colored the readings of the accelerometers although the nature of the resonances is not given.

The authors concluded that simultaneous slosh and vibration tests are effective ways to test external fuel tanks. Structural weak points were uncovered by the testing. The slosh requirements appear to be satisfactory in that the frequency of slosh, about 0.3 Hz corresponds to maneuver rates of fighter airplanes; but the vibration requirements of 0.020 and 0.032 in. double amplitude at about 2000 cpm are obviously not environmentally consistent. The testing for 10 minutes of a full tank following the 25 hour test should be justified. Nevertheless, combined slosh and vibration testing appears necessary for proving the integrity of fuel tanks.

It appears that the U.S. Air Force has an obligation to revise and update Specification MIL-T-7378A (USAF).

3.11 "Advantages of Time Domain Techniques in Testing Equipments," by D.R.B. Webb, Royal Aircraft Establishment, U.K.

The above title identifies the subject of an informal talk given by Mr. Webb in place of the presentation of a paper that had been withdrawn earlier.

Mr. Webb discussed the case for using time-histories for qualifying equipment to resist gunfire. He questioned the reality of test requirements that were based on the use of frequency domain techniques, and he questioned the validity of failures that occurred after such tests. He felt that aircraft gunfire was highly deterministic, and that it might be more realistic to simulate its effects by matching a measured time-history. Furthermore, gunfiring vibration time-histories may be easily simulated in the laboratory in real time.

Discussion following his presentation brought out many questions or comments. One question concerned the changes in the gunfire vibration simulation procedures in MIL-STD-810D. Dr. Burkhard answered that Method 519 in MIL-STD-810D will permit several test methods because no single method is superior. Another question concerned the repeatability of gunfiring vibration time-histories between different flights of an aircraft. Comments on the realistic simulation of this environment included the desirability of using separate sinusoidal and random vibration tests and the use of test requirements that are derived from measured time-histories and transfer functions. - R. Volin, Shock and Vibration Information Center, U.S.

3.12 "The Structual Dynamic Interface Required for Developing Helicopter Target Acquisition Systems," by S. T. Crews, U.S. Army AVRADCOM.

This paper describes the development of the installation of a complex Target Acquisition Data System in the nose of a Hughes AH-64 helicopter (Fig. 20). This system consists of an optical sensor, a TV sensor, a forward looking infrared sensor (FLIR), a laser range finder designator and spot tracker, all mounted on a stabilized platform. Auxiliary equipments were to be installed in the avionics bay. The size and complexity of the installation required structural modifications with sufficient stiffness to avoid resonances with major helicopter rotor induced forcing functions. This is described as controlling "interfacing" amplitudes.

An original requirement for vibration qualification testing of bulkhead mounted equipment was based on MIL-STD-810B category (c) testing but this was abandoned at the recommendation of the bidding contractors as being unrepresentative of the helicopter environment. A vibration survey on a prototype helicopter was carried out and the results were worked into a multi-level, limited environmental test that was conducted on equipments prior to flight to prove performance and air worthiness. Competing contractors were required to demonstrate performance in flight in a "Fly Before Buy" program. Just prior to this competition, additional vibration surveys on prototype AH-64's were conducted and a Life Cycle Vibration Qualification Test was developed. One provision of this specification which was negotiated with the contractors was that electronic components not mounted in the nose of the helicopter were to be qualified to MIL-STD-810C category (c) requirements. The earlier developed limited environmental test was used as a quality assurance screening test for production units.

Another installation discussed was a Stand-off Target Acquisition System (SOTAS) in a Sikorsky EH-60C helicopter. The system features an extension-retraction pedestal mounted in the fuselage that carries an 18 foot long reflector equipped with radar fixed horns. In use, the reflector extends about 21 inches below the belly of the helicopter and can rotate through a full 360°; the helicopter landing gear is retracted 45 inches during the operation of the system. The antenna and reflector are very stiff to minimize relative deflections. In this program the following steps were taken: (a) allowable vibrations at the fuselage-pedestal junction were "stringent"; (b) The antenna-pedestal and associated equipment rack were to have no "as mounted to the helicopter" resonant vibrations near helicopter blade passage frequencies and their three higher harmonics; (c) the antenna-pedestal structure was to have a fatigue life of 20,000 hours; (d) all equipment items were to pass MIL-STD-810C vibration tests; (e) mathematical models (NASTRAN) were to be confirmed by ground shake tests; (f) flight loads and vibration surveys of a full-scale structural dynamic model of the antenna-pedestal were to be run and (g) a full-scale, single-article, fatigue test was to be conducted on the pedestal.

Installations of large, heavy, complicated subsystems such as targeting and tracking systems require extensive aircraft structural redesign and modifications. Certainly structural dynamics plays a central role in this work. The author's foreboding about the part that equipment qualification test standards play in this work is dispelled by noting that MIL-STD-810C is called out for qualifying equipments in the two programs presented in his paper.

3.13 "Approach in Dynamic Qualification of Light Helicopters Stores and Equipments," by D. Braun and J. Stoppel, Messerschmitt-Bolkow-Blohm, Germany.

This paper describes the qualification of two anti-tank missile launchers as installed on a light military helicopter, the MBB BO-105 (Figs. 21, 22). Each missile launcher is attached to pylons which become integral with the fuselage structure. The unmodified helicopter has no resonant modes near the 4/rev frequency, about 28 Hz. How, then does the addition of the launchers affect this relation?

First, the launchers themselves are qualified by vibration tests in accordance with the French Air Norme-7304 (5-500 Hz, 5g/2g cycling tests for 2½ hours, each axis, and 20 minutes dwell each resonance, respectively, Fig. 23). Then design calculations were made of the fundamental resonant mode of the loaded pylon. This showed that the resonant frequency was below the 4R helicopter forcing frequency. The pylons were manufactured and shake tests were conducted on the isolated launcher-pylon combinations. The vertical and longitudinal (helicopter axes) resonances were 16.5 and 22.3 Hz respectively. The question is, what will the frequencies be when the pylon launcher is attached to the helicopter fuselage?

To answer this, a loads/stress finite element model of the helicopter was utilized, in which NASTRAN multi-level, substructuring methods were used. Results showed symmetric and unsymmetric modes, and the effects of fuselage elasticity reduced the vertical and longitudinal natural frequencies to 12.21, 13.12 Hz vertical and 17.97, 20.37 Hz longitudinal. It was also indicated that two modes existed near the 4R frequencies, a 2nd pitching mode and a torsional mode of the fuselage. These modes apparently occur without the pylon-launchers. An investigation to what extent these modes might be excited by the 4R forcing function was not conducted. Flight tests showed that in no case did 4R responses exceed 1g. It was concluded from this that the 2g limit set by AIR NORME 7304 was met.

3.14 "The Dynamic Qualification of Equipment and External Stores for Use with Rotary Wing Aircraft," by G. M. Venn, Westland Helicopters, U.K.

In this paper, the author first traces the development of vibration testing at Westland from 1962 to the present. Originally, the requirements were a resonance search by sinusoidal sweep from 5 to 150 Hz; and an endurance test at fixed frequencies, these being the 4th rotor order (the fundamental of rotor blade passage frequency) and the first and second tail rotor orders. Amplitudes were defined by an amplitude vs. frequency curve that varied from about ±½g at 10 Hz to ±10g at 150 Hz. The author did not indicate what the test durations were. In 1966, two zones in the helicopter were established, one within the power region and one outside of it. The resonance search by sweeping was extended to cover the frequency range from 3-500 Hz for equipments in the power region zone; from 3-150 Hz for equipment outside the power region zone, and from 3-175 Hz for equipments externally mounted. The endurance tests were at the fixed frequencies of two main rotor harmonics, the fundamental and second harmonic of main rotor blade-passage frequency. In addition, there was a 400 Hz high-frequency test for equipment in the power region zone. Torsional vibration tests of input shafts to mechanically driven equipment were included. Amplitudes were taken from the same curves as previously.

In 1975, the equipment qualification test specification was overhauled and made consistent with British Standard 3G.100 and RTCA DO 160. The helicopter was divided into six zones, although this number can depend on a particular helicopter design. The different zones (Fig. 24) reflect the various levels of vibration in the helicopter. The amplitude-frequency range curves are shown in Fig. 25. These curves define the amplitude of the initial resonance search using a sweep rate not greater than 1 octave per minute. The range of operating rpm's of helicopter engines and main and tail rotors together with their drive shafts and gearings, including power operated equipments, is not large, 5-10%, and each of them and their harmonics define bands of frequencies, called "frequency avoid bands". Any equipment resonances that occur in such bands are removed by structural modifications, or if this is not practical, an endurance test is run at the resonant frequency and amplitude so discovered. Endurance tests are carried out in two stages, a sine sweep and a constant frequency test. For the sweep test, the appropriate curve in Fig. 25 is used for a one-hour sweep along each axis at a sweep rate of one octave per minute. For the fixed frequency endurance test, the amplitudes and frequencies are given in Fig. 26. The test times shown are divided equally among each of the three perpendicular directions. A final resonance search is made to determine any changes in resonant frequencies. Fig. 27 shows some environmental data on two types of external stores and the amplitude-frequency curve for zone X, externally mounted equipments. The curve X defines endurance test levels of ±3g for rotor induced vibration frequencies. Because of the great dominance of periodic over random vibration in helicopters, Westland will not accept equipment tested by a random vibration test. Fixed frequency is insisted upon at least as far as endurance testing is concerned. A strong recommendation is made to establish by experimental work a reliable correlation between sinusoidal and random vibration presumably for the fatigue failure mechanism. Some work in this area has been done in the sonic fatigue area. The relevance of this work to the equipment environmental problem should be investigated.

3.15 "Application of Modal Synthesis Techniques for the Dynamic Qualification of Wings with Stores," by E. Breitbach, DFVLR-AVA Goettingen, Germany.

The author of this paper develops the mathematical background of Modal Synthesis techniques that is tailored to the solution of problems involving aircraft wings carrying external stores. The problems are those concerning flutter clearances for aircraft that must carry large combinations of stores of many varieties. Modal synthesis techniques, which can determine the mode shapes and frequencies of large discrete-mass dynamic systems by breaking a system into parts, analyzing the parts and then reassembling the total system using selected modal information is well adapted to the multiple store flutter clearance problem.

In his paper the author develops modal correction and modal coupling methods. In the modal correction method, incremental stiffness and mass corrections are made to the mass and stiffness matrices of the

matric equation of the overall configuration. The modal parameters and frequencies for the configuration are obtained from a ground vibration test (GVT). These tests must be conducted carefully so that normal modes are measured; in the event pylon stiffness changes are involved, additional static tests are required to obtain terms for the pylon stiffness matrices.

The modal coupling method is an alternative way to attack the wing-store problem. Three classes of coupling are defined: flexible, rigid and mixed coupling. In flexible coupling, a coupling matrix describing the elastic properties of the coupling is calculated and is an added term to the system stiffness matrix in the equations of motions of the two interconnected substructures. Rigid coupling requires zero relative motion in the interface and introduces difficulties in the general case. These can be avoided sometimes by the use of mixed coupling for which stiffnesses vary among the degrees of freedom from flexible to rigid.

Fig. 28 shows the main steps in establishing a mathematical model of the wing-store system. It can be described as: (1) a GVT on configuration A, the clean wing with dummy mass; (2) a GVT (or static test) on configuration B, the store/pylon subsystem, (3) removal of the dummy mass effects by modal correction calculations and (4) coupling of subsystem B to the clean wing by rigid coupling techniques.

The effects of non-linearity usually show up as variations in resonance frequencies with amplitude. Usually, the non-linearities occur in pylon connection points at wing and store junctions. The non-linearities are introduced into the equations of motion of the linear system by adding to the stiffness matrix of the system a non-linear modal correction matrix that contains elements having the non-linear properties of the pylon connection. These properties are determined by equivalence based upon amplitude-dependent stiffness and damping. The equivalences were determined by a co-quad analysis using an electrical circuit analog whose outputs yielded the equivalent stiffnesses and damping losses for an hysteresis type non-linearity.

The author concludes his paper with an account of the rather poor agreement that occurred between wind tunnel flutter test results on a half-wing model of a variable-sweep wing and corresponding non-linear flutter calculations. An explanation was found in the observation that the wing showed different vibratory responses depending on whether it was forced from the store or the wing. Physical insight was gained by an analysis of an oscillator shown in Fig. 29. Two third-order differential equations are involved and are solved for the relative motion across the damper for the two types of excitation. By keeping the equivalent damping the same in each case, the vibration behavior varied completely with the way the system was excited.

The author concludes that modal coupling methods and modal correction methods are effective procedures for dealing with the dynamics of wing and stores.

3.16 "STOL Aircraft Structural Vibration Prediction from Acoustic Excitation," by B. F. Dotson, Boeing, and J. Pearson, Air Force Wright Aeronautical Laboratories, U.S.

The authors of this paper are concerned about the acoustic fields generated by Upper Surface Blowing (USB) flap-type STOL airplanes and the vibratory response of the structure to these fields. The flaps suffer direct impingement of exhaust gases on their upper surfaces and the severe flap vibrations as well as the noise are transmitted across the fuselage structure to the interior of the airplane. Vibration prediction methods were needed for this new and novel environment.

Exterior fuselage noise spectra measured at three fuselage locations on a Boeing YC-14 USB STOL airplane (Fig. 30) are given in the paper for take-off and for USB flap positions, but the authors do not indicate where the measuring locations on the fuselage were nor what the flight conditions were corresponding to the USB flap positions. In general, the spectra peaked between 50-80 Hz at 130 to 150 db sound pressure level. The method used to predict the acoustic field is given by Ref. 12. Figure 31 shows results of predicted and measured sound pressure levels for a point on the fuselage during ground run-up at maximum engine thrust. Agreement seems quite satisfactory.

Predicted and measured vibration of the flap structure is shown in Fig. 32. One of the major difficulties in vibration prediction according to the authors is estimating structural damping. The agreement with the measured data depends upon a structural damping coefficient g=0.15. This seems to be very high.

In developing a vibration prediction method for the fuselage, several models of the structure were set up; three of these used finite element techniques with varying mesh sizes corresponding to low frequencies, 25-100 Hz, to intermediate frequencies, 100-300 Hz, and to frequencies above 300 Hz. Two models were set up using periodic structure theory (Ref. 13). Measured acoustic data were used to calculate the structural response. At the same time the noise data were taken, fuselage response data were measured at three locations, one on a stringer, one on a frame and one on a skin panel. Comparisons between predicted and calculated responses appear satisfactory; however, vibrations appear to be overpredicted at low frequencies (Fig. 33). The predicted vibration for the model using periodic structure theory, the frame stiffened cyclinder model, was not satisfactory. For further work, the finite element analysis approach to structural modeling was adopted

A further study was made of the Quiet Short Range Aircraft, a small STOL airplane having a gross weight of 22,700 kg (50,000 lbs). Predictions of acceleration psd spectra for the flap and fuselage modeled by finite elements showed good agreement with measured data.

The authors concluded that an FEA model approach to vibration prediction is a feasible technique during preliminary design. The problem of modeling for the correct level of structural damping would appear to remain.

3.17 "Gunfire Blast Pressure Predictions," by R. M. Munt, A. J. Perry and S. A. Moorse, Royal Aircraft Establishment, U.K.

This paper was scheduled to be given by the senior author, R. M. Munt. In his absence, Mr D. R. B. Webb, Royal Aircraft Establishment, presented the paper.

The paper describes a method for determining the blast pressures, Figs. 34, 35, about the muzzle of a gun from the properties of the propellant exhaust. As set out in the Conclusions in the paper, the authors have extended a present theory which is based upon an analogy of gun blast with an explosive releasing energy at a constant rate and having strong directional effects due to the momentum of the propellant gas flow (Ref. 14). The method developed by the authors modifies the present approach by placing the apparent center of the explosion in the "shock bottle" at a distance of about six gun calibers from the muzzles instead of at it (Fig. 36). Pressure predictions based on this model agree well with experimental data for a 7.62 mm (30 caliber) rifle (Fig. 37) and a 27 mm aircraft gun.

Gun blast measurements were also obtained experimentally on a surface near the gun muzzle. It was found that these can be predicted with reasonable accuracy if regular acoustic reflection occurs, but in the region of Mach reflection the agreement is poor particularly for small distances between the line of fire and the reflecting surface. Mach reflection occurs when the reflected waves tend to coalesce with the incoming waves. Under such circumstances the pressure on reflecting surfaces can be as high as four to eight times the pressure of the incident waves, instead of the usual pressure doubling on rigid surfaces that intercept acoustic waves.

3.18 "Taped Random Vibration Acceptance Testing of Avionic Equipment," By E. F. Baird, Grumman, U.S.

In this paper, the author started with the generally accepted premise that random vibration is more acceptable than sinusoidal as a screen for workmanship problems in avionic equipment. Mr. Baird outlined an open loop test technique using synthetic random tapes which retains the characteristics of random vibration but does not require the costly closed-loop control equipment. Total energy is controlled by adjusting overall rms levels with some compromise acknowledged in spectral distribution between test items.

In the discussion following the paper it was asked if any items in excess of 60 pounds had been tested in this manner. The author stated that items up to 300 pounds had been successfully tested using a 30,000 pound shaker. A question as to what ratio of qualification test level to service environment was used, the author replied that the test was not intended to be a fatigue test but that typical levels were 6g rms random (.04 g^2/Hz). -- D. A. Underhill, General Dynamics, U.S.

4. CONCLUSIONS

4.1 The Meeting on the dynamic qualification of external stores showed a wide interest in this area as evidenced by the many contributors and their papers. An equal interest was shown in vibration analysis techniques and vibration level prediction.

4.2 Heavy stores (170-1300 kg) both large (5 m long) - low density - and medium size experience vibration levels in flight at low frequencies (4-200 Hz) four to ten times lower than that given in Standards.

4.3 Lightweight stores (32-90 kg) - instrument pods - experience vibration levels at low frequencies in high q flight and maneuvers larger than vibration levels given in Standards.

4.4 Because of the extensive parameterization scheme followed in MIL-STD-810's (U.S.), these Standards have been used as a prediction tool in individual cases although the Standards are based upon "worst case" instances covering all possible equipment installations in broad classes of vehicles. Cases where MIL-STD-810C levels exceed individual measured environments are to be expected.

4.5 Cases where the test levels in Standards are found to be lower than levels derived from ground or flight tests merit serious consideration. These cases are largely those of external stores carried on aircraft during maneuvers in which the low frequency, lowly damped structural modes of the aircraft are excited. This condition has not yet been taken into account in the Standards.

4.6 For externally carried aircraft fuel tanks, slosh and vibration tests as specified in MIL-T-7378 (USAF) are effective as qualification tests except that the level and frequency of the applied vibration are not realistic.

4.7 Gunfire vibration levels measured in flight are in some cases substantially lower than those indicated in the Standards.

4.8 In two cases, the British Tornado MK-1 airplane and the U.S. F-16, vibration levels measured in ground gunfiring tests showed good agreement with levels measured in flight. Effects of aircraft speed and maneuver accelerations on gunfiring vibration were not strongly evident.

4.9 Structural stiffness and damping may be important factors in the attenuation of vibration with distance from the guns.

4.10 Gun mounting reactions are important forcing functions in addition to gun muzzle blast.

4.11 Advances in gun blast prediction theory and improved blast deflector design are needed.

4.12 Acoustic testing not only of stores but of other equipments has considerable merit. The ability to reach frequencies well above 2,000 Hz may be valuable for testing equipments in which miniaturized electronic components are incorporated.

4.13 Sine-random test equivalences are not generally agreed upon neither as to the magnitudes of the constants that are involved nor as to the validity of the damage accumulation process for equipments. Agreement ranges from acceptance to outright rejection.

4.14 Test level augmentation, or amplitude exaggeration methods and the concomitant test time compression factors are central to defining endurance test levels. This definition depends upon damage accumulation considerations. Agreement in this area is important.

4.15 Common test set-ups, test procedures and test durations are needed for comparing the results of qualification testing.

4.16 Field failure data are important in determining the effectiveness of the equipment qualification process.

5. RECOMMENDATIONS

Some general suggestions are as follows:

- Revise Standards where applicable to include additional store categories, e.g., low density stores, electronic pods.

- For external stores, consider extending the frequency range down to 4 Hz to encompass excitation of the low frequency structural modes of the airplane.

- Update MIL-SPEC T-7378A (USAF) in regard to realistic vibration inputs for external-fuel-tank slosh and vibration tests. Justify or delete the final, 10-minute full-tank vibration test.

- Study revisions to gunfiring test methods to include (a) structural stiffness and damping as gun-blast attenuation-with-distance parameters and (b) gun mount reaction forcing functions as vibration sources for equipment.

- Study advances in gun blast theory and in design of gun blast deflectors.

- Confirm the correlation between the damage incurred under random and sinusoidal testing that is applicable to aeronautical equipments.

- Standardize test set-ups, test procedures and test durations to achieve comparability in qualification test results.

- Reconvene the Specialist Meeting at some appropriate time in the future to determine the results of "tailorability" and other revisions to international Standards.

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LIST OF ILLUSTRATIONS

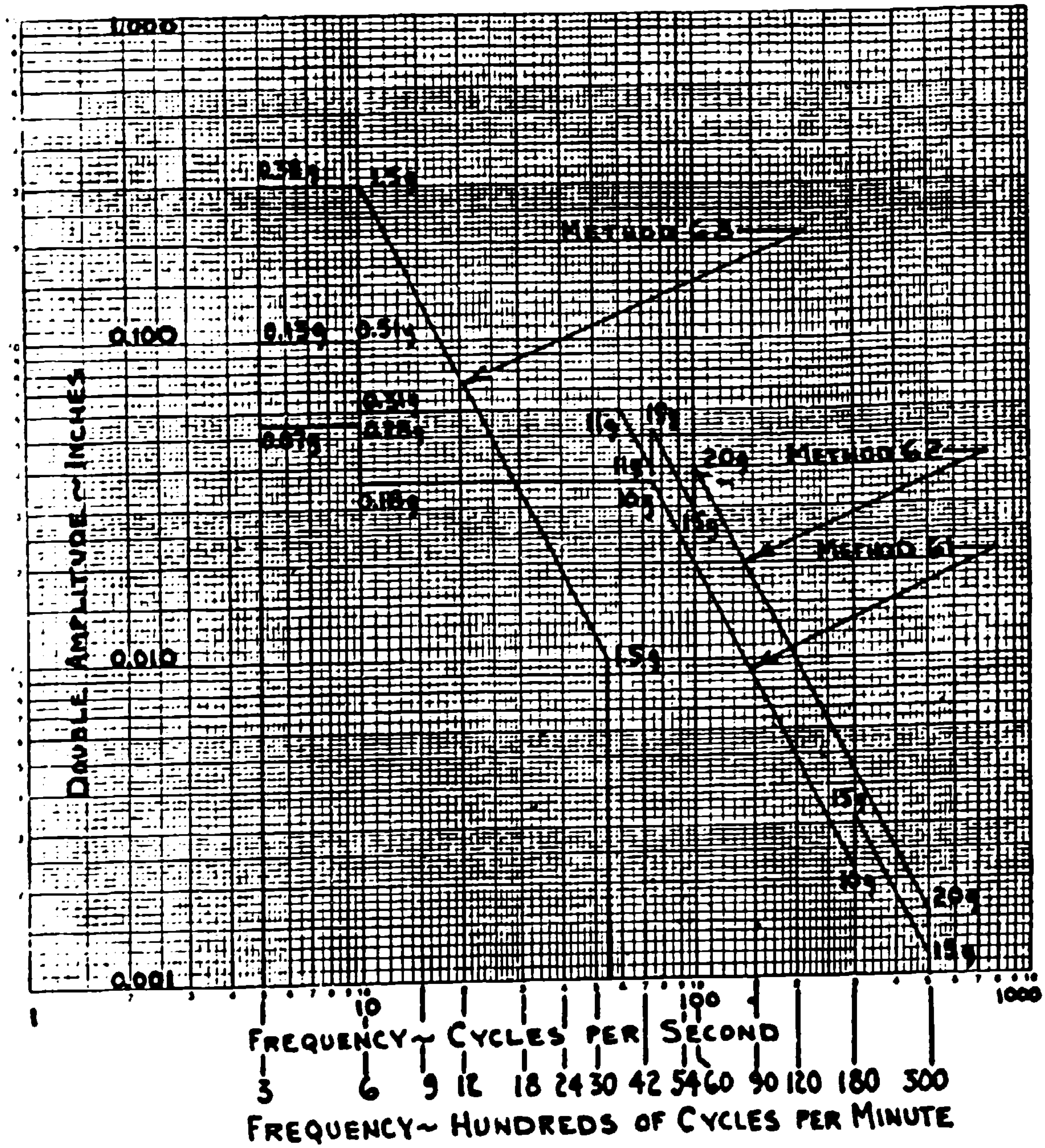


Fig. 1 Range curves for vibration tests in AAF Specification 41065 (1945)

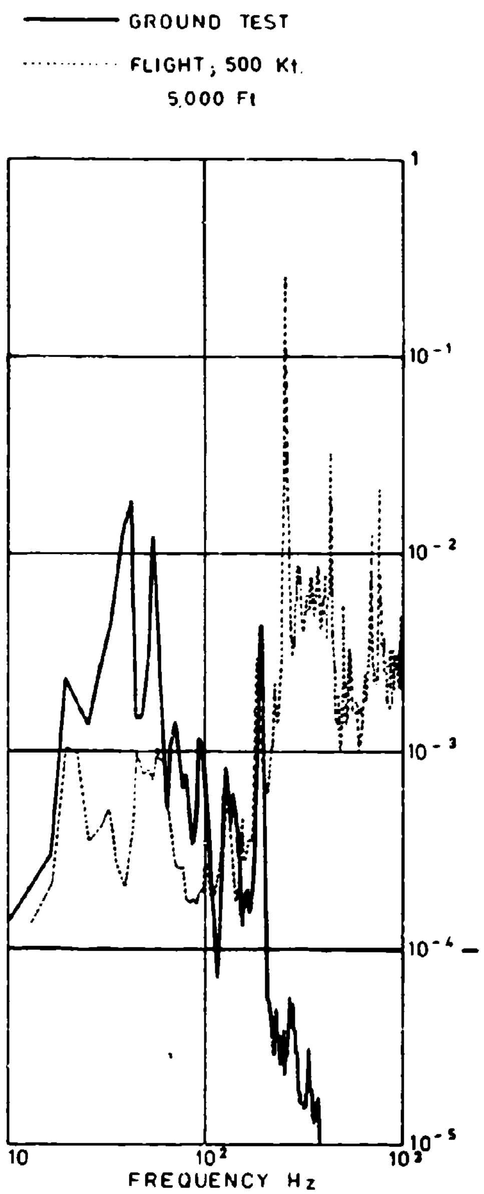


Fig.2 Low frequency response, ground test vs flight, store No.1

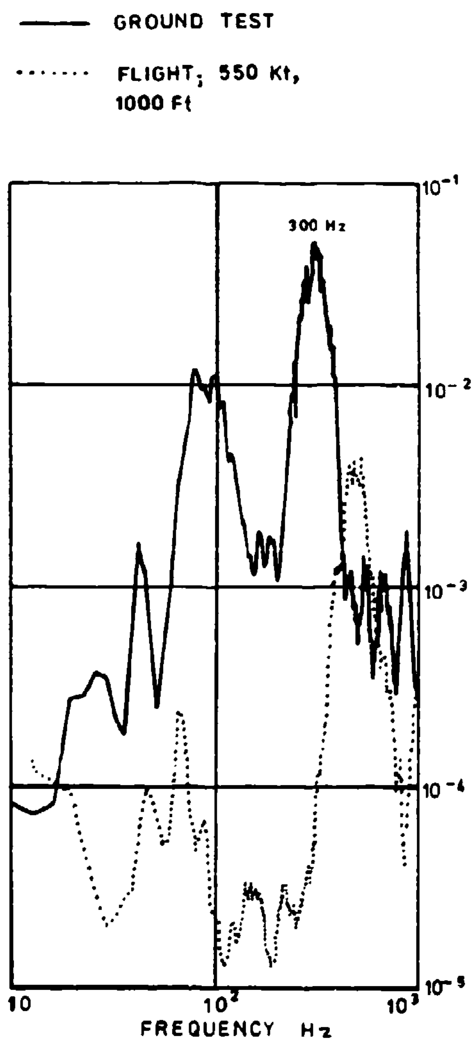


Fig.3 Low frequency response, ground test vs flight store No.2

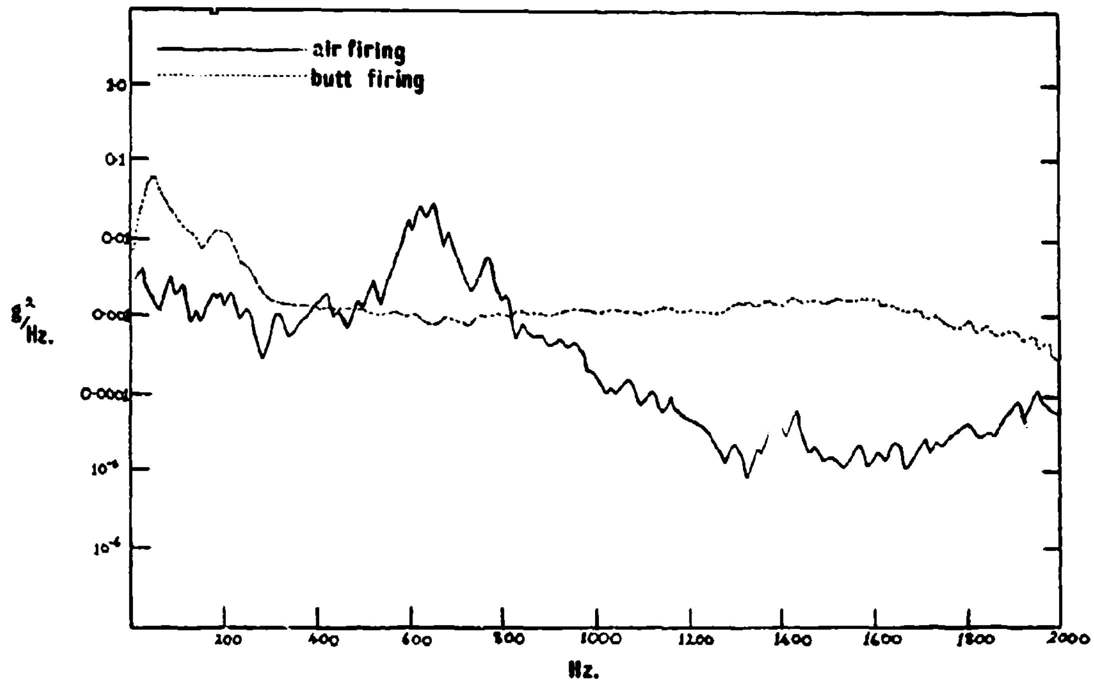


Fig.4 Comparison of gun and butt firing levels

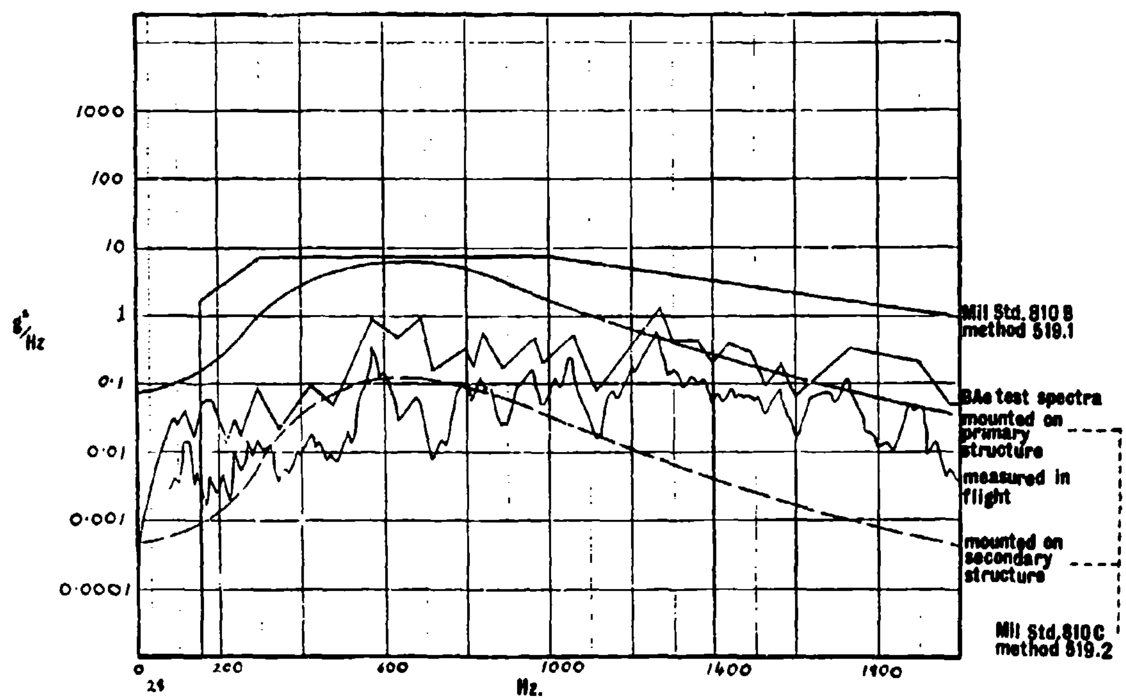


Fig.5 Comparison of test spectra with standards, typical equipment, vertical direction

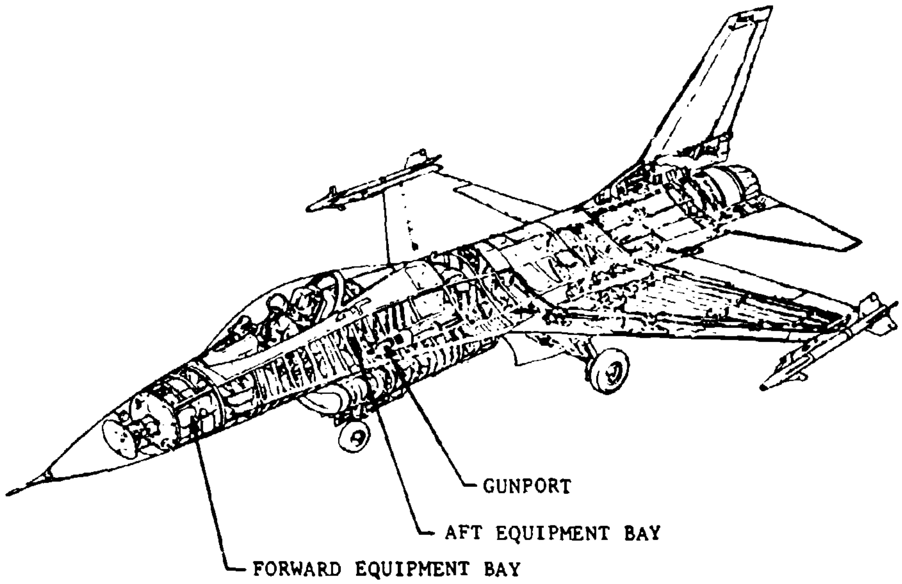


Fig.6 F-16 Structural configuration

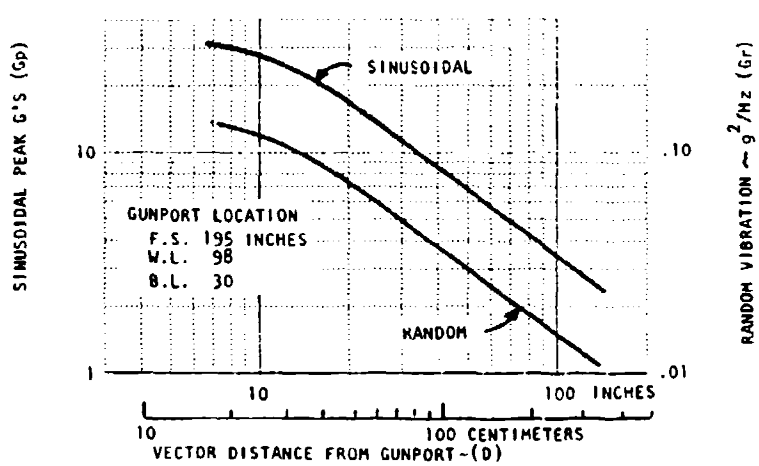


Fig.7 Vibration vs distance from gunport

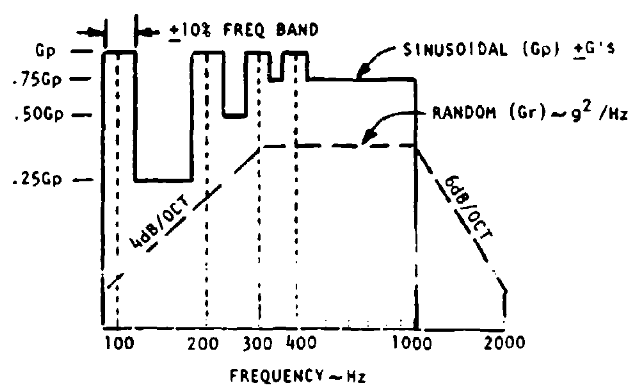


Fig.8 Frequency spectrum for combined random and sinusoidal vibration

AIRCRAFT ZONES	TEST LEVELS MAX PSD g^2/Hz		
	ENDURANCE	PERFORMANCE	A
1A - Fwd Fuselage	.033	.025	.02
1B - Aft Equip. Bay	.053	.040	.02
2A - Center Fuselage	.093	.070	.04
2B - Wing Except Tip	.186	.140	.04
2C - Wing Tip + Launcher	.186	.140	.04
3A - Aft Fuselage	.330	.250	.04
3B - Engine Mounted Equip.	-	-	-
3C - Hor. Tail & Vert. Tail Except Tip	.370	.280	.04
3D - Vertical Tail Tip	.370	.280	.04
SUPPLEMENTARY SINUSOIDAL TEST	Peak g	Peak g	
2C - Wing Tip + Launcher (4-10 Hz)	7.5	5.0	
3D - Vertical Tail Tip (15-20 Hz)	10.0	7.5	

Fig.9 F-16 Qualification test levels

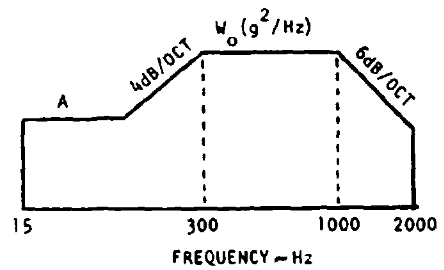


Fig.10 Frequency spectrum for random vibration test

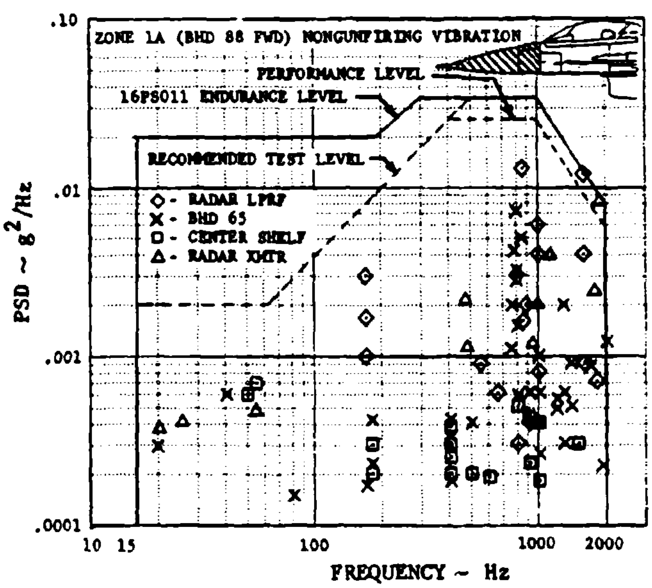


Fig.11 Vibration levels in forward equipment bay – F-16

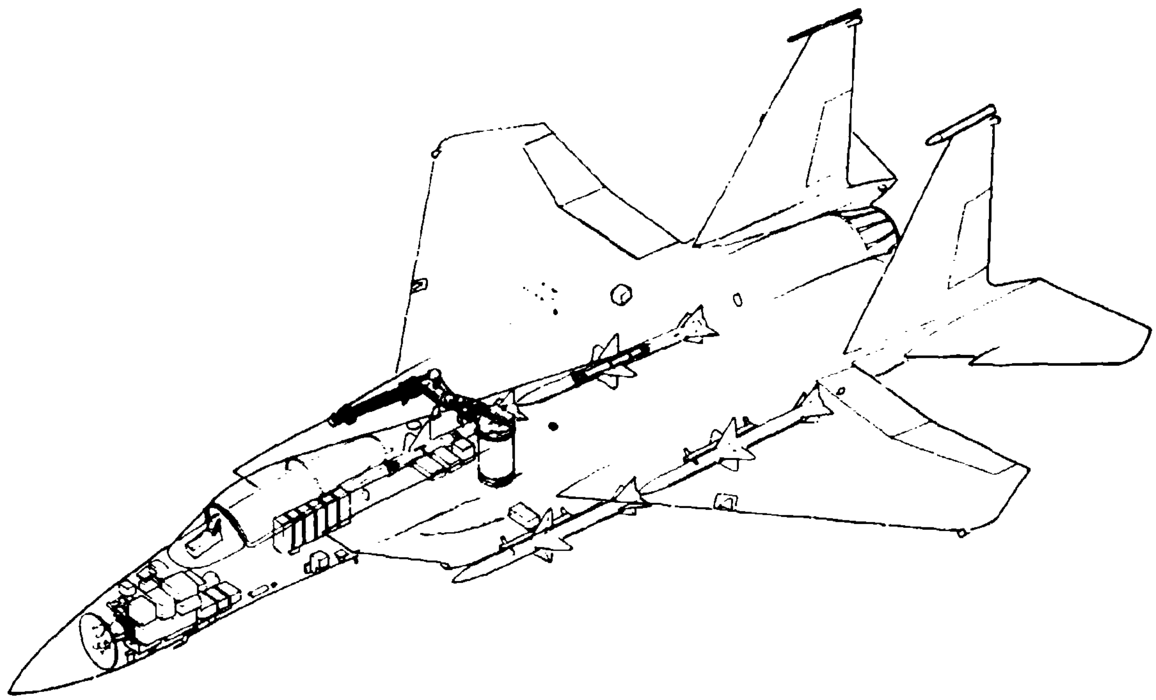


Fig.12 F-15 internal arrangement

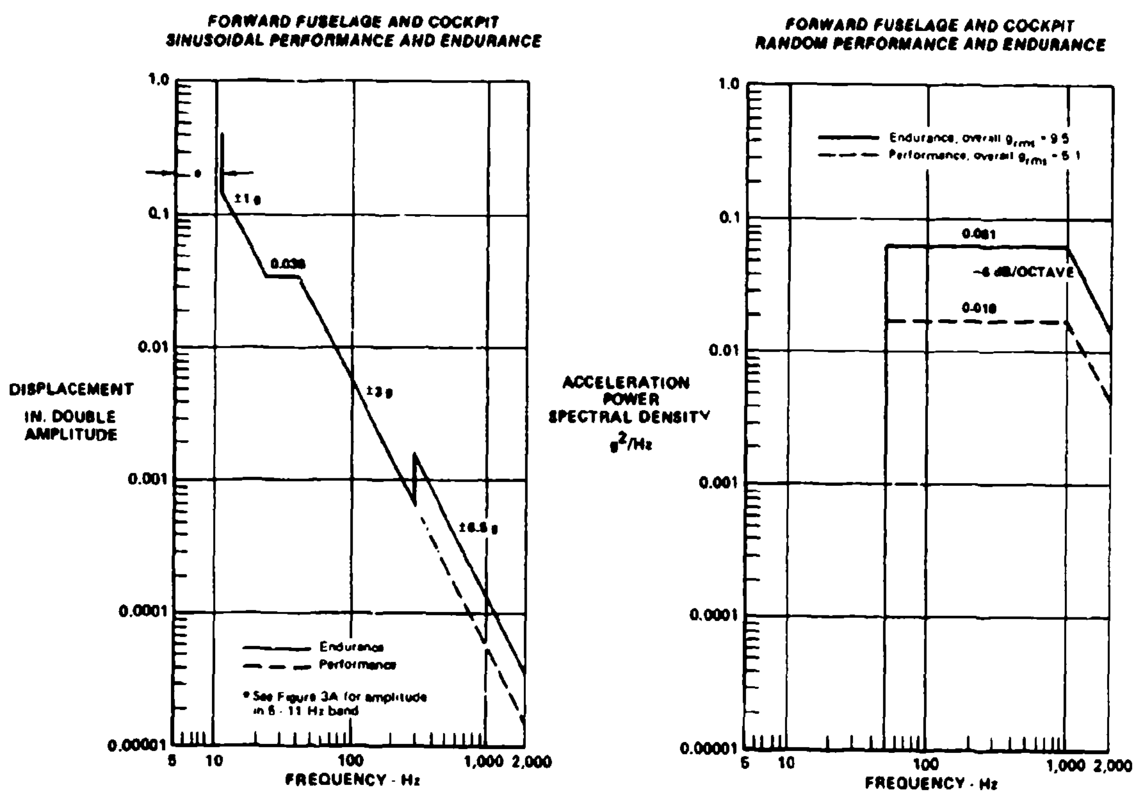


Fig.13 F-15 predicted vibration test levels

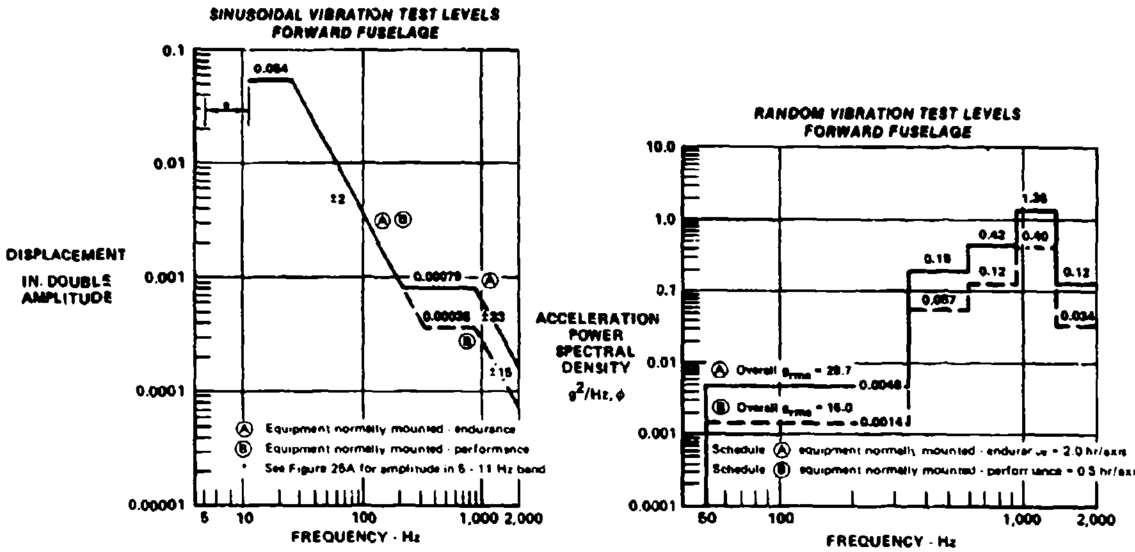


Fig.14 F-15 measured vibration test levels

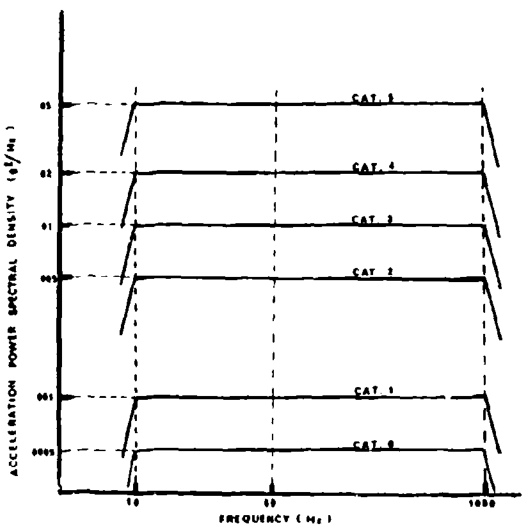


Fig.15 Standard BS 3G100 vibration categories – random

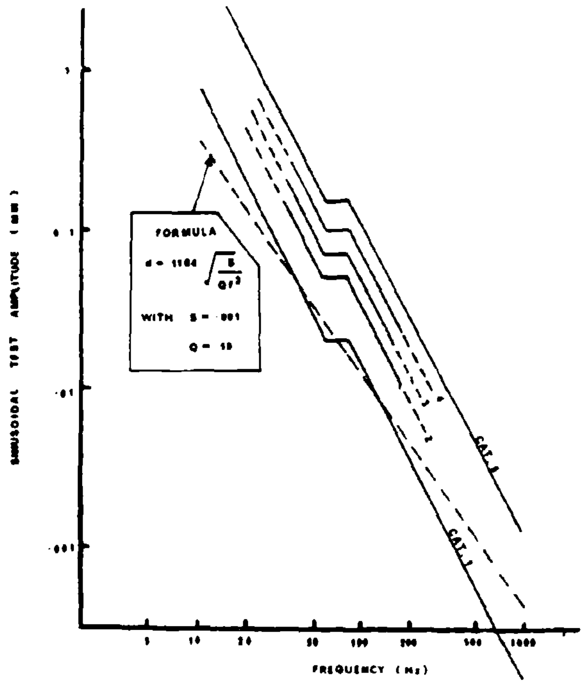


Fig.16 Standard BS 3G100 vibration categories – sinusoidal

	MIL-STD 810 C	BS36.100	AIR 7304
TEST SEQUENCE	FUNCTIONAL TEST ENDURANCE TEST FUNCTIONAL TEST	RESONANCE SEARCH ENDURANCE TEST RESONANCE SEARCH	RESONANCE SEARCH ENDURANCE TEST RESONANCE SEARCH
EXCITATION TYPE	RANDOM: (15) 20- MAX. 2000 Hz	SINE SWEEP: 10-1000 Hz RANDOM: 10-60 Hz, 60-1000 Hz	SINE SWEEP: 5-2000 Hz RANDOM: 10-2000 Hz
TEST TIME	1/2 + 1 + 1/2 HOURS/AXIS	≤ 50 HOURS FOR 10-60 Hz ≤ 50 HOURS FOR 60-1000 Hz	2 1/2 HOURS/AXIS
LEVEL DEPENDENT ON	EQUIPMENT LOCATION MAX. AIRSPEED ENGINE NOISE EQUIPMENT WEIGHT NO. OF MISSIONS ETC.	EQUIPMENT LOCATION VIBRATION CATEGORY DEFINED BY FLIGHT CONDITIONS	EQUIPMENT LOCATION EQUIPMENT WEIGHT

Fig.17 Standards comparison

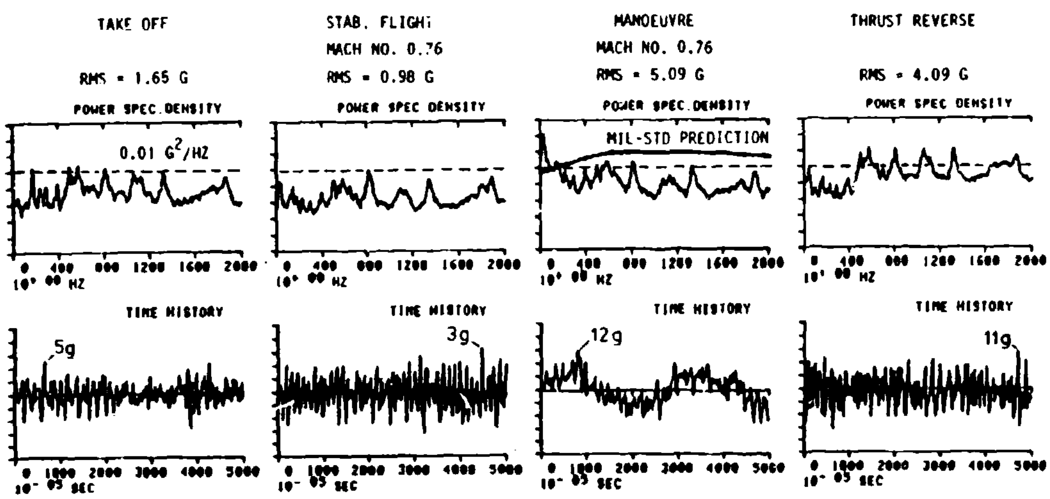


Fig.18 Spectra and time histories of different flight conditions – instrument pod

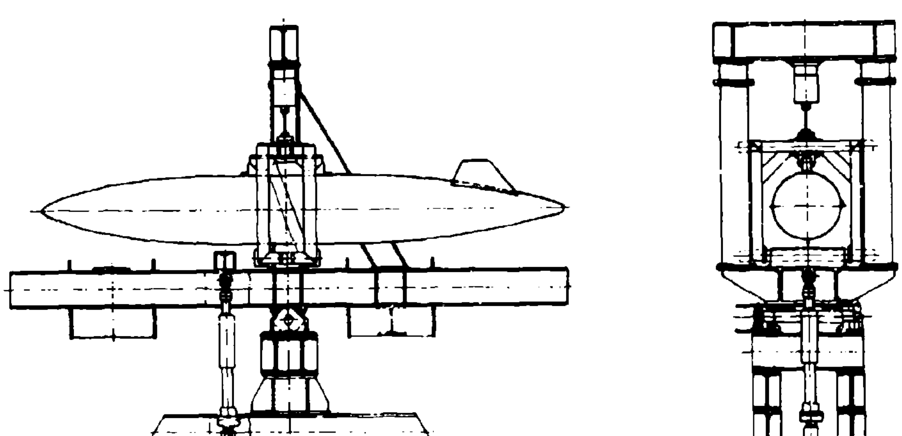


Fig.19 Test rig

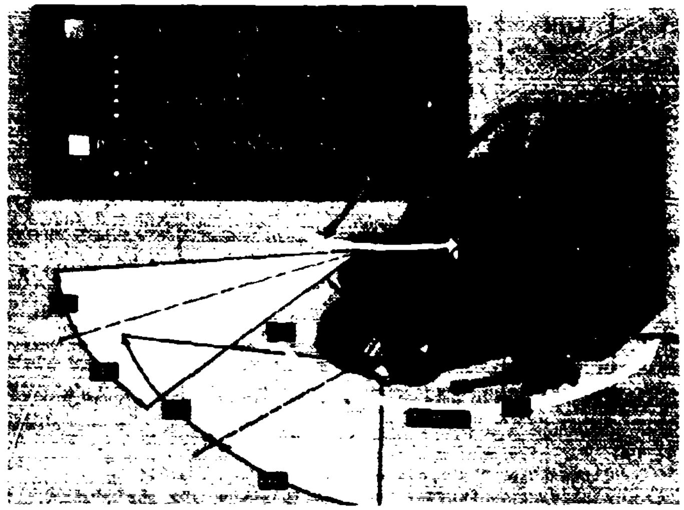


Fig.20 Target acquisition designation system/pilot night vision system (TADS/PNVS) for AH-64 helicopter

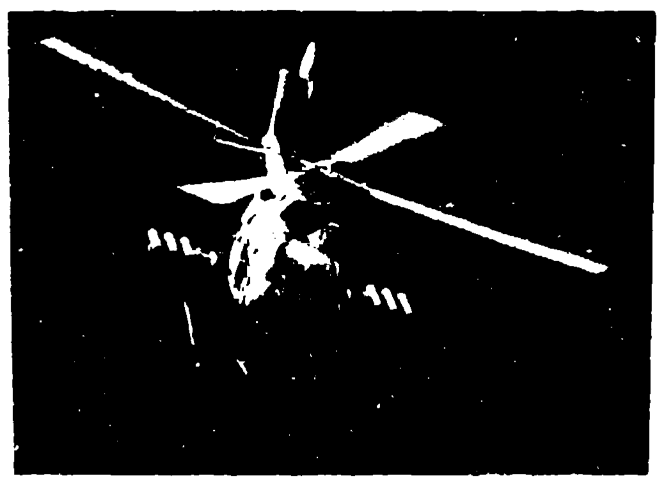


Fig.21 BO-105P helicopter

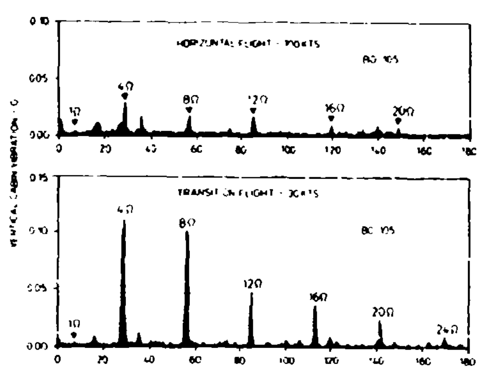


Fig.22 Typical vibration spectrum of BO 105 helicopter

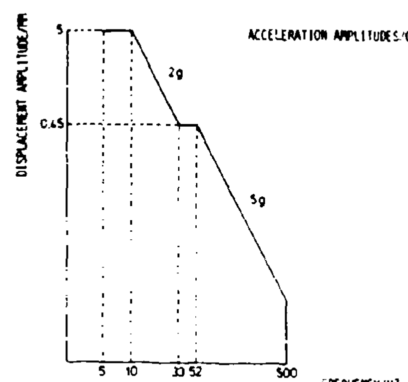


Fig.23 Vibration test curve (Air Norme 7304)

Aircraft Region	Main Fuselage	Instrument Panels and Isolated Racks	Instrument Racks – Not Isolated	On/in close proximity to Engine
Curve	N	P	N	W
Aircraft Region	Under-carriage Sponsons	Tail Cone and Tail Pylon	Gearboxes (See Note (i))	Externally Mounted Equipment
Curve	V	V	W	X

Note: (i) (a) For equipment mounted on the Tail Rotor and Angle gearboxes a composite curve of V and W shall be used, i.e. Curve V shall be followed from 5Hz until it intersects Curve W and then continued on Curve W.

(b) For equipment mounted on the Main Gearbox the vibration envelope does not preclude the possibility of gearbox excited vibration in the range of 3000 Hz to 30,000 Hz.

Fig.24 Zoning scheme

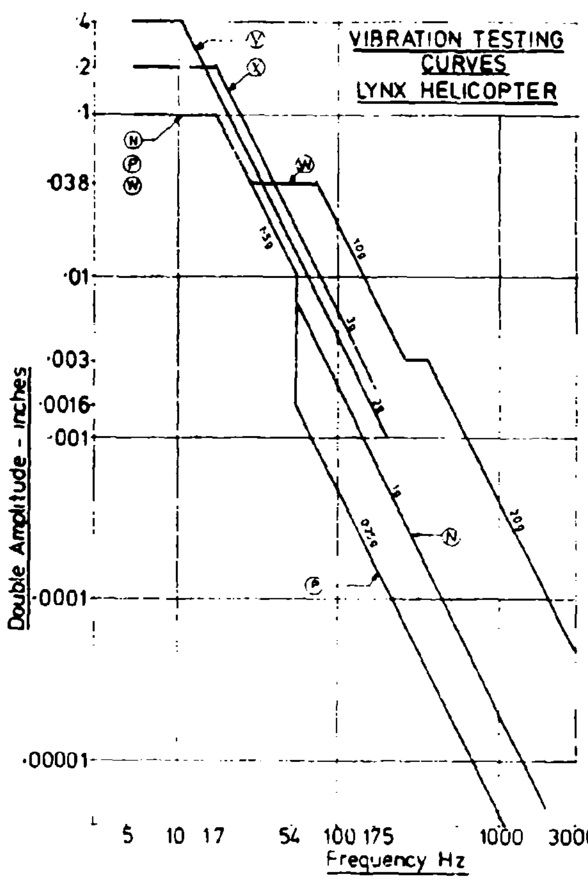


Figure 25

(a) <u>Programme for equipment tested to curves N, P, V or X</u>

3×10^6 cycles @ 22 Hz = 37.9 hours

3×10^6 cycles @ 44 Hz = 18.9 hours

3×10^6 cycles @ 128 Hz = 6.5 hours

(b) <u>Programme for equipment tested to curve W</u>

3×10^6 cycles @ 22 Hz = 37.9 hours

3×10^6 cycles @ 44 Hz = 18.9 hours

3×10^6 cycles @ 128 Hz = 6.5 hours

3×10^6 cycles @ 500 Hz = 1.7 hours

(c) For equipment driven by external means the 128 Hz test of programme (a) or (b) shall be replaced by one of 3×10^6 cycles at its own drive frequency at a level given by the specified test curve.

Fig.26 Endur^nce test times

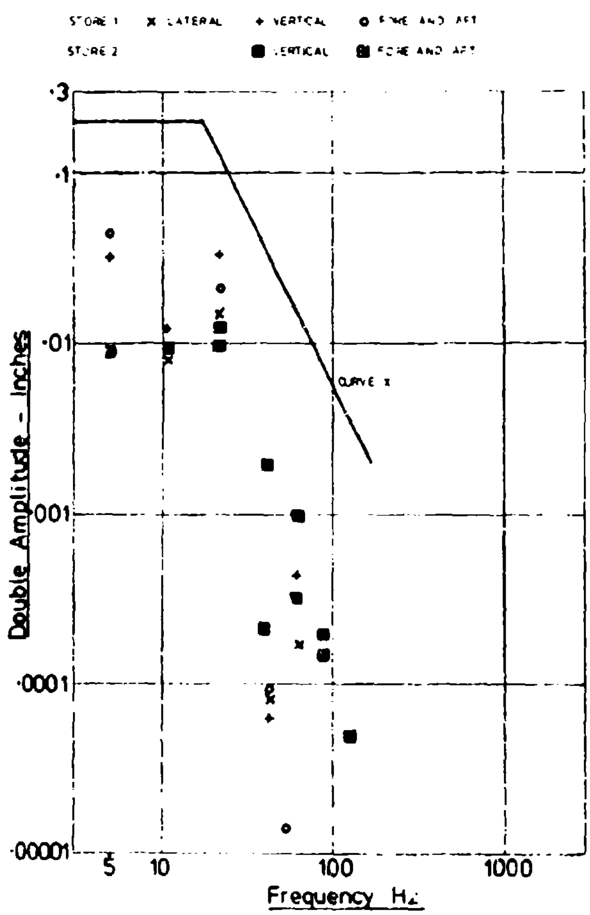


Fig.27 External stores, curve X, 140 Kts

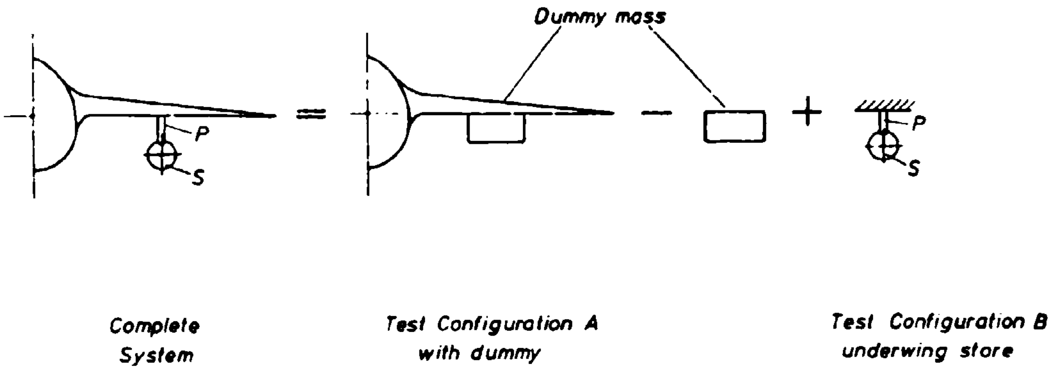


Fig.28 Wing-with-store system

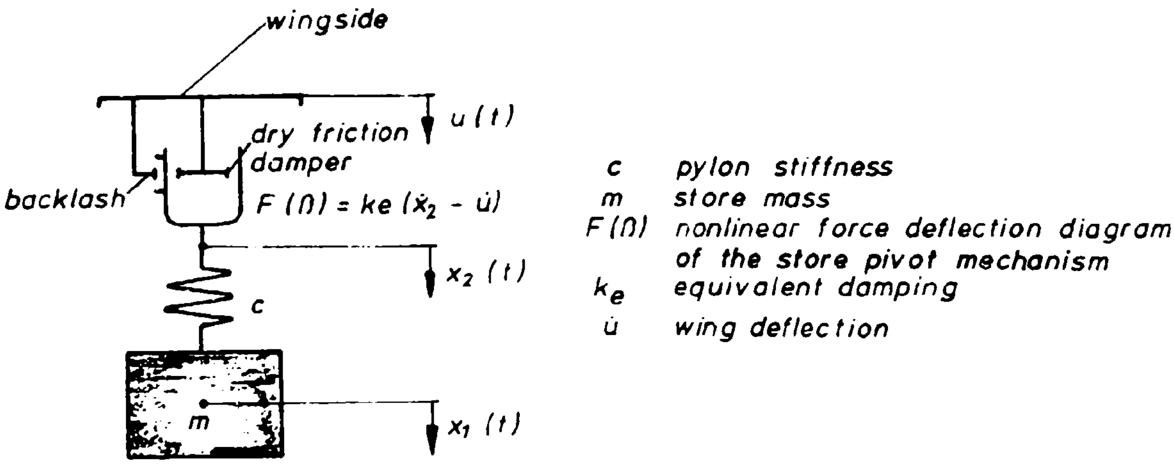


Fig.29 Sketch of an oscillator with one and one-half degrees of freedom

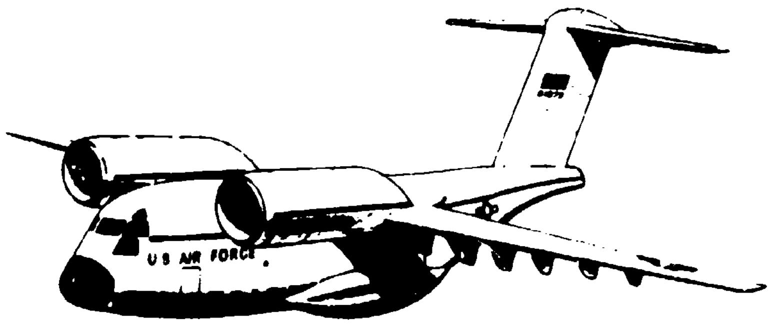
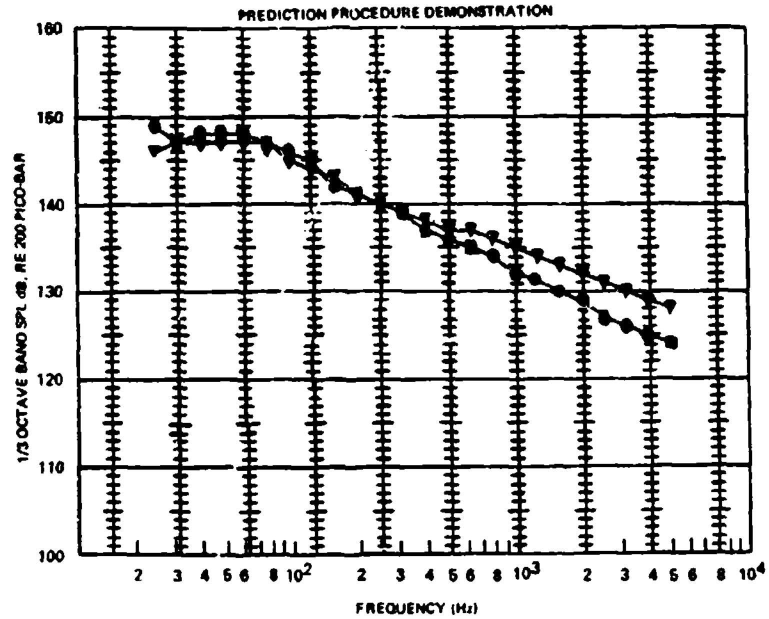


Fig.30 YC-14 prototype



PLOT SYMBOL	X-DUCER NO	COND NO	ALT (FT)	SPEED (FPS)	N1 (RPM)	VMIX (FPS)	USBFA (DEG)	OVERALL (dB)
●	M16	7132	0	42	3640	1100	0	157
▼	M16	7132						156

NOTES

● MEASURED TOTAL NOISE DATA

▼ PREDICTED TOTAL NOISE

Fig.31 Sound pressure level for a point on the fuselage

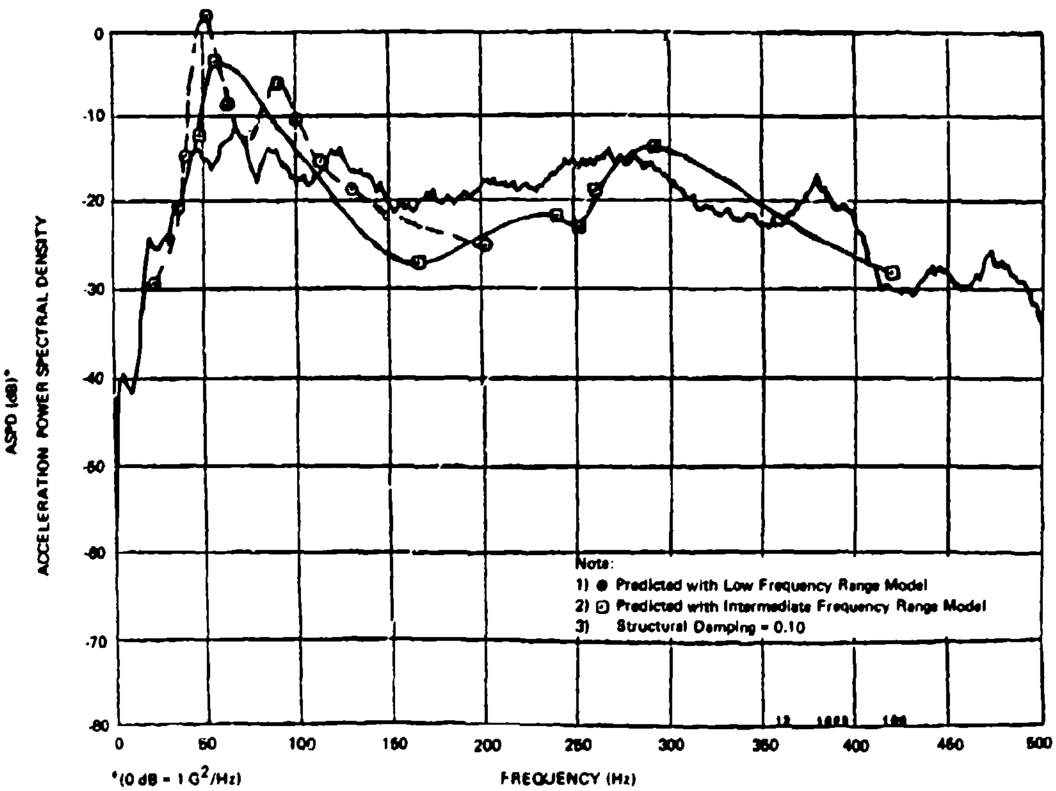


Fig.32 Measured and predicted fuselage vibration

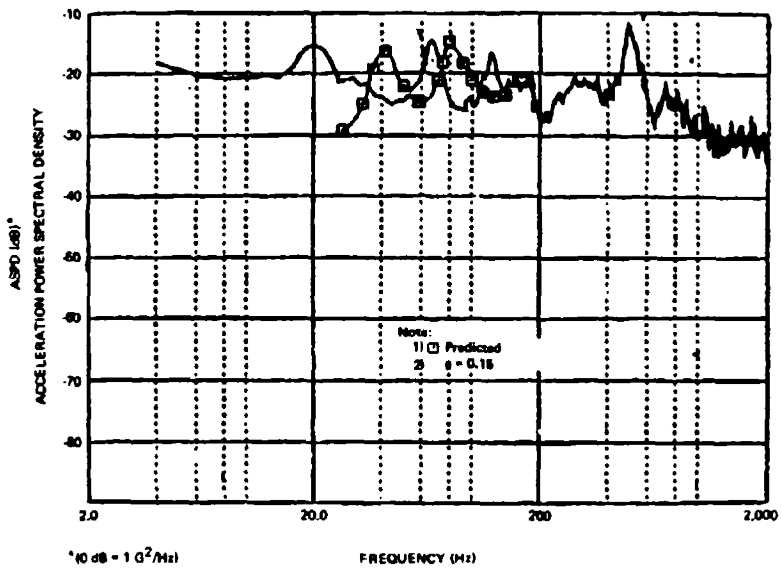


Fig.33 Measured and predicted USB flap vibration

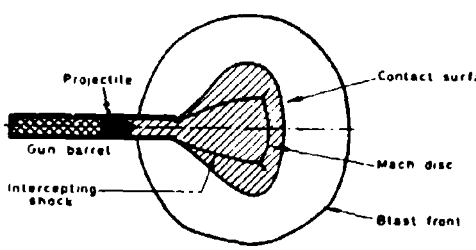


Fig.34 Precursor blast field

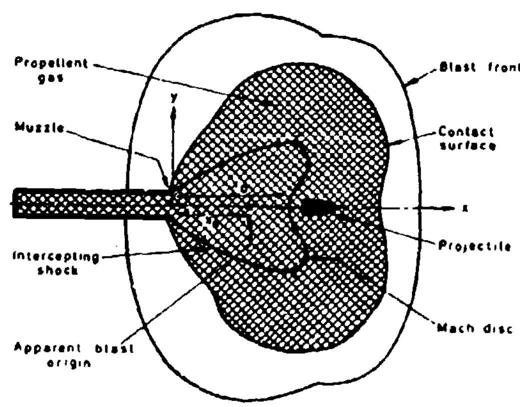


Fig.35 Propellant blast field

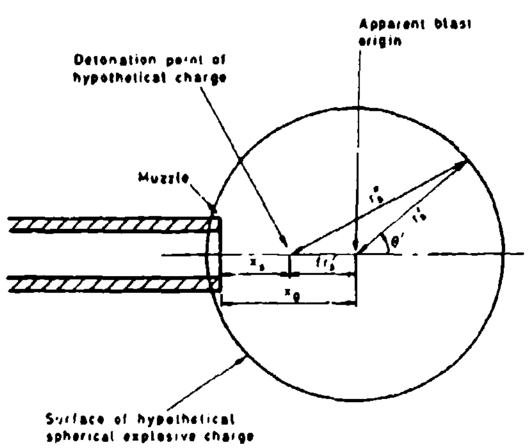


Fig.36 Spherical charge model

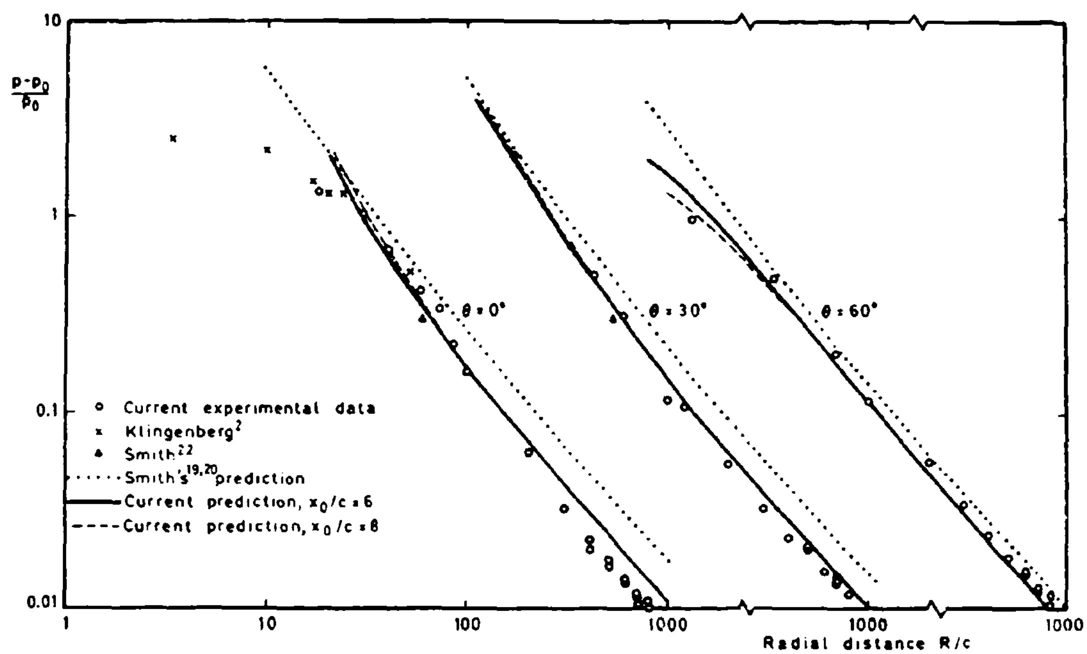


Fig.37 Comparison of predicti ;ns with experiment for radial distribution of max. overpressures, 7.62 mm rifle

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7. Presented at

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Howard A.Magrath	July 1982

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Dynamic response	Vibration

14. Abstract

At the 53rd Meeting of the Structures and Materials Panel of AGARD, a Specialists' Meeting on "Dynamic Environmental Qualification Techniques" was held on 28–30 September 1981. It was the purpose of the Specialists' Meeting:

- To review the state-of-the-art of dynamic qualification techniques and test methods presently applied for military aircraft and helicopters, particularly when carrying external stores;
- To exchange technical information in this field between all NATO countries;
- To review the background and intentions of related Military Standards publications;
- To try to formulate a common basis for dynamic structural requirements and substantiation procedures.

In this Technical Evaluation Report, summaries of the 17 papers presented at the Meeting, and published as AGARD CP-318, are given. Some thoughts on these papers are outlined and general suggestions are made with regard to revisions of existing Military Standards and further improvement and standardization of dynamic qualification procedures.

This Advisory Report was sponsored by the Structures and Materials Panel of AGARD.

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